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Effects of Water Sprinklers on the Performance of Low Level AFFF Aircraft Hangar Fire Suppression Systems

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A series of full-scale fire tests was conducted to evaluate the effect that overhead water-only sprinklers have on the effectiveness of a low level AFFF fire suppression system. The combined overhead water-only sprinkler and low level AFFF system is being considered as a new protection scheme for U.S. Navy aircraft hangars. The results show that the operation of overhead water sprinklers up to 10.2 Lpm/m^2 (0.25 gpm/ft^2) does not degrade the performance of a low level system during AFFF discharge (4.0 Lpm/m^2 (0.1 gpm/ft^2)). Based on the results of these tests, the design criteria for Navy hangar protection may be revised to incorporate AFFF application from only the low level system, combined with overhead closed-head guide response water sprinklers.

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Effects of Water Sprinklers on the Performance of Low Level AFFF Aircraft Hangar Fire Suppression Systems

1.0 BACKGROUND

Current Navy design standards for protecting large aircraft hangars include both overhead and low level aqueous film forming foam (AFFF) extinguishing systems [1]. The overhead AFFF system typically consists of standard closed head sprinklers that are zoned within areas defined by draft curtains. In some existing installations, the overhead systems are open head deluge systems. The low level system typically consists of multiple high flow monitors (e.g., 1893 Lpm (500 gpm)). The low level AFFF and overhead deluge sprinkler systems are activated by separate detection systems (heat detection or UV/IR).

Due to high costs incurred from damage of aircraft and electronics resulting from accidental discharges of the overhead AFFF system in addition to environmental concerns associated with AFFF, the Navy is exploring alternate suppression techniques. The proposed approach would replace the overhead foam suppression system with a closed-head water sprinkler system. The ground level AFFF delivery system would become the primary means of fire suppression, and the overhead sprinklers would be used to cool adjacent aircraft and protect the structural integrity of the hangar. The time delay in activating the overhead system would also be minimized through the use of quick response sprinklers. This time delay has already been quantified in previous studies [2].

The rational for replacing the overhead AFFF system with a water sprinkler system is twofold. First, AFFF has a greater potential than water for damaging the aircraft electronics if the cockpit is open, and second, the higher costs associated with installing, maintaining and restoring the overhead AFFF system after an accidental discharge can be prohibitive. After discharge, the entire suppression system must be overhauled, cleaned and the foam concentrate supply replaced before the system can be put back in service. Additionally, there are environmental concerns associated with the discharge of aqueous film forming foam (AFFF) [3].

The concern with combining overhead water sprinklers with a low level AFFF extinguishing system is the potential negative effects the water spray may have on the foam blanket. Overhead sprinklers operating on the foam blanket might impact both the extinguishing capability of the foam and its ability to resist burnback. When AFFF is applied over a flammable liquid spill or fire, the foam blanket forms a vapor barrier, suppressing the release of flammable vapors. If the integrity of the foam blanket is damaged, the vapors may escape and ignite. Potentially, the water droplets from the overhead water sprinkler system could have sufficient

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momentum and density to degrade the stability of the blanket. If the foam blanket stability is compromised, the vapor barrier may be lost, and the potential for burnback and re-ignition is increased. The application of water can also dilute the foam blanket, causing it to break down faster which may result in the release of flammable vapors.

The Navy initiated this investigation to evaluate the capabilities of an aircraft hangar fire suppression system consisting of a low level AFFF extinguishing system and an overhead water sprinkler system. The design parameters of a proposed low level AFFF system that would eliminate high flow foam monitors (using instead, numerous lower flow nozzles mounted flush with the hangar floor) is the subject of a separate study [4].

This report describes the full-scale fire test results of the Aircraft Hangar Fire Protection System Evaluation conducted at Underwriters Laboratories, Inc. (UL). The tests were conducted in two phases. The first phase [5] served to bound the effects of various system parameters. The second phase [6] quantified system performance over a range of fire scenarios.

2.0 OBJECTIVE

The objective of the investigation was to evaluate the effect overhead, water-only sprinklers have on the effectiveness of low level AFFF fire suppression systems. The effectiveness of the combined systems was based on its ability to extinguish a large spill fire, as well as the ability to resist burnback. The spill fire was continuously supplied with burning fuel from a shielded running fuel fire. The combination of the supply of burning fuel, the radiation from the shielded running fuel fire and the degradation of the foam blanket resulting from the water spray of the overhead sprinklers contributed to the fire burning back over the fuel spill surface.

3.0 FIRE SCENARIO

A significant hazard associated with an aircraft hangar is the ignition of a fuel spill resulting from a broken fuel line or a ruptured fuel tank. The resulting fire might consist of both a three- dimensional running fuel fire shielded by the wing of the aircraft and a large pool fire produced by the spilling fuel. Upon detection of the fire by the UV/IR detectors, the low level AFFF fire suppression system would be activated. If the overhead temperatures significantly increased, the overhead sprinklers would also be activated. For this fire scenario, the low level AFFF suppression system would be required to extinguish the pool fire resulting from the fuel spill and prevent the fire from spreading to areas other than under the wing of the aircraft. The proposed system would be required to prevent fire spread/burnback for a minimum period of ten minutes (i.e., the design duration of the AFFF concentrate and the estimated time for the fire department to respond to the fire). The system would not be expected to extinguish the running fuel fire shielded by the aircraft wing. The potential to burn back across the fuel surface is a function of the addition of burning fuel, radiation from the shielded fire and the degradation of the foam blanket resulting from the water spray of the overhead nozzles.

The proposed fire suppression system consists of both a low level AFFF extinguishing system and an overhead quick response closed head water sprinkler system. Upon the onset of a fire, at a minimum, the low level AFFF extinguishing system would be activated either automatically using flame detection or manually. If the fire spreads quickly, producing a large fire before the fire is detected and AFFF is discharged, both the overhead water and low level AFFF system may be activated simultaneously or in sequence. The possibility also exists that sprinkler activation may be delayed until after the low level AFFF system has begun discharging due to the time required for a hot layer to develop and to the thermal lag of the sprinkler. It is these fire scenario and system variables that were mocked-up and evaluated during this fire investigation.

4.0 TEST DESCRIPTION

The fire scenario(s) consisted of a three-dimensional running fuel fire that created a spill fire on the concrete floor around the fire apparatus. The fire apparatus consisted of a fuel cascade located inside of a 0.9 m x 0.9 m (3 ft x 3 ft) fuel pan. As the fuel cascaded down the apparatus, the pan filled and began to overflow, producing the spill fire. The severity of the scenario was varied by changing the fuel flow rate and the location of the fuel supply to the apparatus. The pan fire and fuel cascade simulated a shielded running fuel fire located under an aircraft wing and was intentionally designed to continue burning after the suppression systems were activated. As stated in NFPA 409 [7], the low level AFFF extinguishing system was required to extinguish the spill fire up to the pan housing and the fuel cascade in less than one minute from system activation. Upon extinguishment of the fire, the system was required to prevent the spill fire from burning back over the pool surface (e.g., 25% of its original size) for a period of ten minutes from system activation. During these tests, the system was evaluated for twenty minutes to determine the robustness of the protection provided by the proposed system.

The test was initiated by filling the pan housing and the fuel cascade with the test fuel (either JP-5 or JP-8) and allowing the pan to burn for one to three minutes prior to activating the running fuel fire. This preburn served to heat the fuel cascade, producing a more severe fire. The cascading fuel continued to flow for a period of twenty minutes or until the test was terminated. Once the resulting spill fire reached a predetermined size (either a specific burn area such as 9.3 m^2 (100 ft^2) or a size based on temperature and radiation measurements), the fire suppression system(s) were activated and observations were made of the time needed to control and extinguish the fire. The fire suppression systems consisted of low level AFFF, overhead water sprinklers and a combination of both.

During a limited number of tests, the overhead water sprinkler system was not activated until five minutes after the low level AFFF extinguishing system. Independent of the activation time, both systems remained activated until the end of the test or until the test was terminated.

The amount of AFFF discharged by the low level system was also varied during the test series. The low level system discharged AFFF for a period of either five or ten minutes at which point the system continued to discharge using water only.

The tests were generally conducted for a period of twenty minutes after the beginning of the AFFF discharge or until the test is terminated. The test was terminated earlier if dangerous conditions arose (the temperatures in the test facility exceeded a critical value) or when the fire burned back to 25 percent of its original size. At the conclusion of the test, the fuel flow was secured, and all residual fires were extinguished using a 3.8 cm (1.5 in) AFFF handline.

4.1 Test Area

The tests were conducted in the large-scale fire test building at Underwriters Laboratories, Inc. (UL) in Northbrook, IL. The building measured 36.6 m x 36.6 m x 16.5 m (120 ft x 120 ft x 54 ft) with a 30.5 m x 30.5 m (100 ft x 100 ft) movable ceiling that was raised to a height of approximately 13.7 m (45 ft). The floor of the test facility was surrounded with a drainage system capable of handling 681,000 liters (180,000 gallons) of effluent. The test area was centered on the west wall of the test facility. The actual test area measured 9.1 m (30 ft) x 6.1 m (20 ft) and was located as shown in Figure 1. A concrete slab 5 cm (2 in) thick was poured in the test area to prevent damage of the test facility floor. The test area was bounded on three sides by berms and by a floor drain on the remaining side. This configuration assured that any effluent that entered the test area was contained and collected in the building drainage system.

4.2 Overhead Water Sprinkler System

An overhead deluge sprinkler system configured in a 2 x 3 grid with nozzles installed with a nominal 3 m x 3 m (10 ft x 10 ft) nozzle spacing was used during these tests (Figure 2). Central Model A pendent sprinklers were used during a majority of the tests. These nozzles were installed approximately 0.3 m (1.0 ft) below the ceiling. In all but two tests, the system delivered either 6.5 Lpm/m^2 (0.16 gpm/ft^2) or 10.2 Lpm/m^2 (0.25 gpm/ft^2) over a test area of 55.8 m^2 (600 ft^2). This corresponded to a total system flow rate of 363 Lpm (96 gpm) and 568 Lpm (150 gpm) respectively. To achieve these application rates at similar system operating pressures of approximately 55 kPa (8 psi), two sizes of sprinkler heads were used. This operating pressure represented the minimum nozzle pressure allowed by NFPA 13 [8]. To deliver an application rate of 6.5 Lpm/m^2 (0.16 gpm/ft^2), a 1.3 cm (0.5 in) orifice was used. For the higher application rate (10.2 Lpm/m^2 (0.25 gpm/ft^2)), a sprinkler orifice size of 1.4 cm (0.53 in) was used. During two later tests, higher water application rates were evaluated 20.4 and 40.8 Lpm/m^2 (0.5 and 1.0 gpm/ft^2). The 20.4 Lpm/m^2 (0.5 gpm/ft^2) was achieved by operating the 1.4 cm (0.53 in) nozzles at 280 kPa (40 psi). The higher application rate (40.8 Lpm/m^2 (1.0 gpm/ft^2)) was achieved using ESFR sprinklers with 1.9 cm (0.75 in) orifices operating at 560 kPa (80 psi).

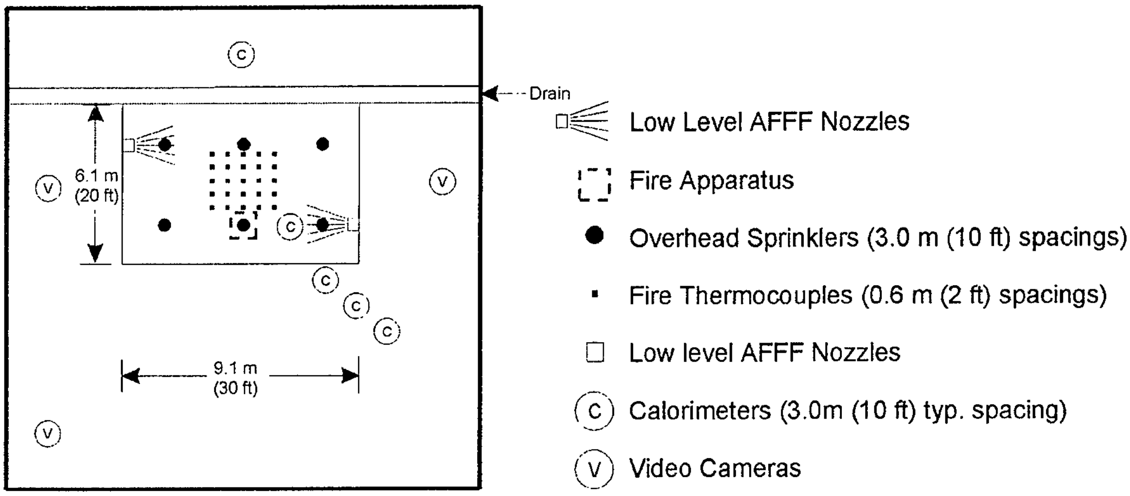


Figure 1 – Test setup

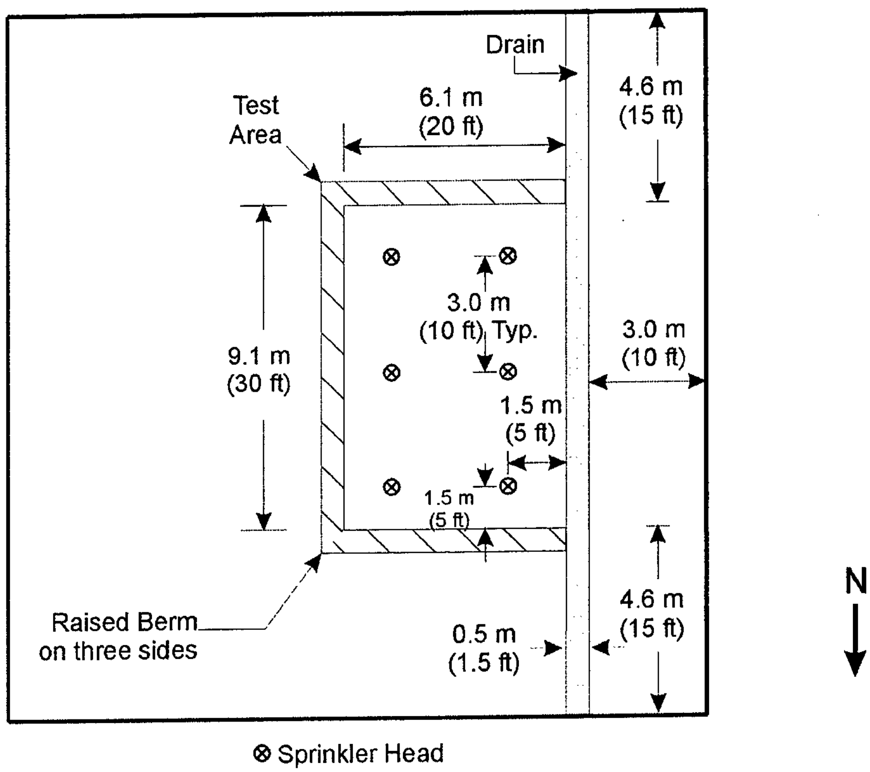


Figure 2 – Plan view of the test area showing sprinkler head locations

The central Model A pendent sprinkler heads are designed to produce a uniform application rate over an area approximately 4.5 m (15 ft) in diameter. The ESFR sprinkler heads have roughly the same area coverage but a majority of the water was concentrated in an area approximately 2.0 m (6.5 ft) in diameter directly under the nozzle. As a result of this localized area with a higher application rate, larger droplet sizes produced by the nozzles, and the higher operating pressures, the spray velocities were significantly greater for the ESFR sprinkler heads than for the standard sprinkler heads.

4.3 Low Level AFFF Extinguishing System

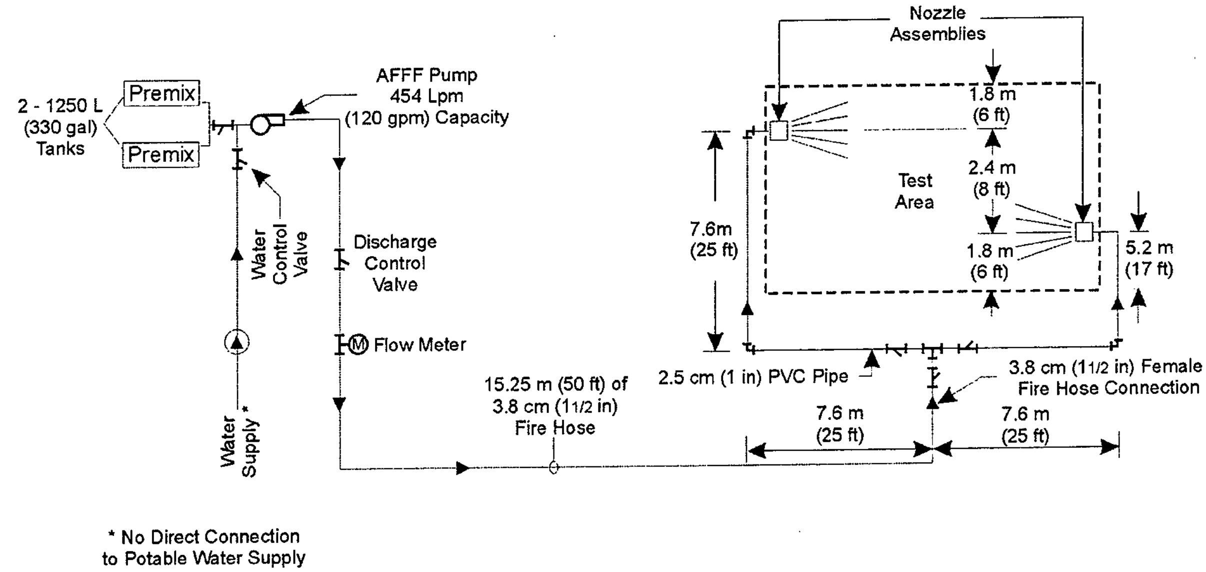
The AFFF delivery system is shown in Figure 3. The system was designed to deliver a nominal application rate of 4.0 Lpm/m^2 (0.1 gpm/ft^2) over the test area through two nozzles located at opposite ends of the test area. This corresponded to a total system flow rate of 230 Lpm (60 gpm).

The low level AFFF system consisted of two 1250 L (330 gal) AFFF storage tanks and a pump with a capacity of 454 Lpm (120 gpm) at a pressure of 690 kPa (100 psi). The system contained a bypass/recirculation line (not shown in Figure 3) which allowed the continuous mixing of the AFFF solution prior to the test. Both the AFFF premixed tanks and a water supply line were connected to the inlet of the pump. Each line contained a ball valve to control the flow into the pump. This setup allowed the switching from AFFF to water at anytime during the test. The discharge from the pump was measured using a turbine flow meter located between the pump and the discharge nozzles. Two sections of 3.8 cm (1.5 in) fire hose were used to connect the pump package to the discharge system.

The discharge system consisted of 2.5 cm (1.0 in) schedule 40 PVC pipe with glued fittings as shown in Figure 3. The nozzles selected for this application were Model NF30050 manufactured by Bete Fog Nozzle, Inc. The nozzles produce a fan shaped spray pattern and flow 113.6 Lpm (30.0 gpm) at a pressure of 276.0 kPa (40 psi). The nozzles were located at opposite ends of the test area and staggered to prevent the spray patterns from over lapping in the center of the area. The nozzles were installed 7.6 cm (3 in) above the test area floor and aimed approximately 10° below the horizontal. The nozzles were aimed downward to reduce the spray pattern coverage (throw) of the nozzle. The nozzle locations and orientation intentionally produced a less-than-optimum low level system. The nozzle assemblies are shown in Figure 4.

4.3.1 AFFF Concentrate

Ansul 3% AFFF concentrate (MIL SPEC qualified [9]) was used during these tests. A total of 1900 liters (500 gal) of AFFF concentrate was required to complete these tests. The concentration of the premixed solution was checked using a refractometer before each test.



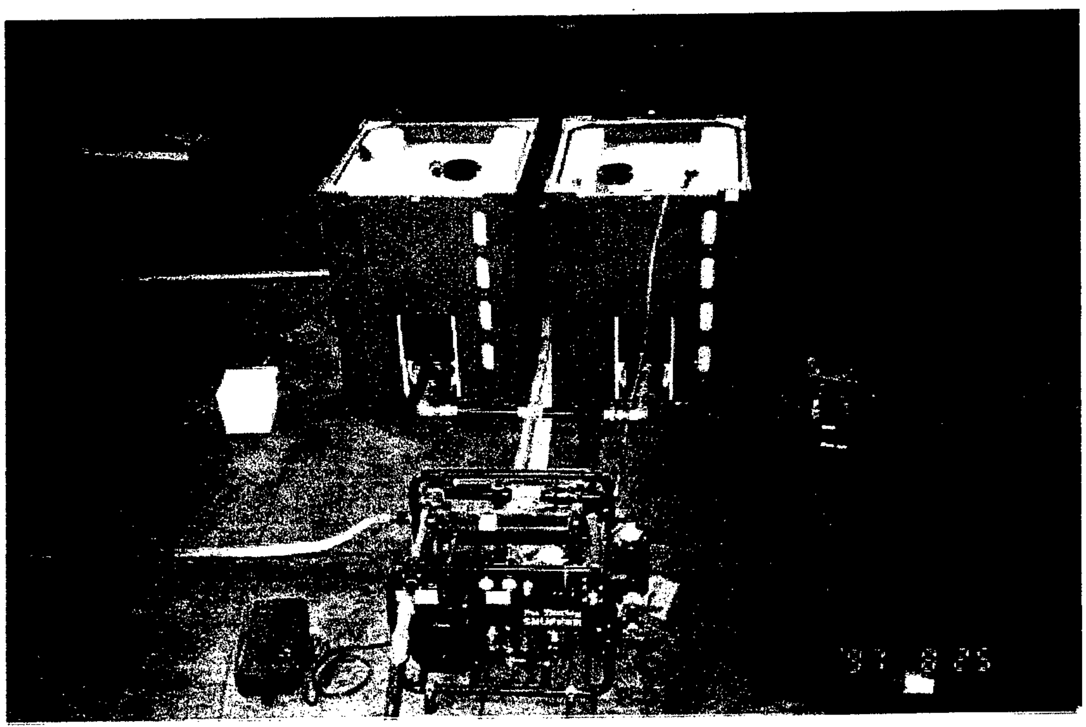


Figure 3 – Low level AFFF extinguishing system

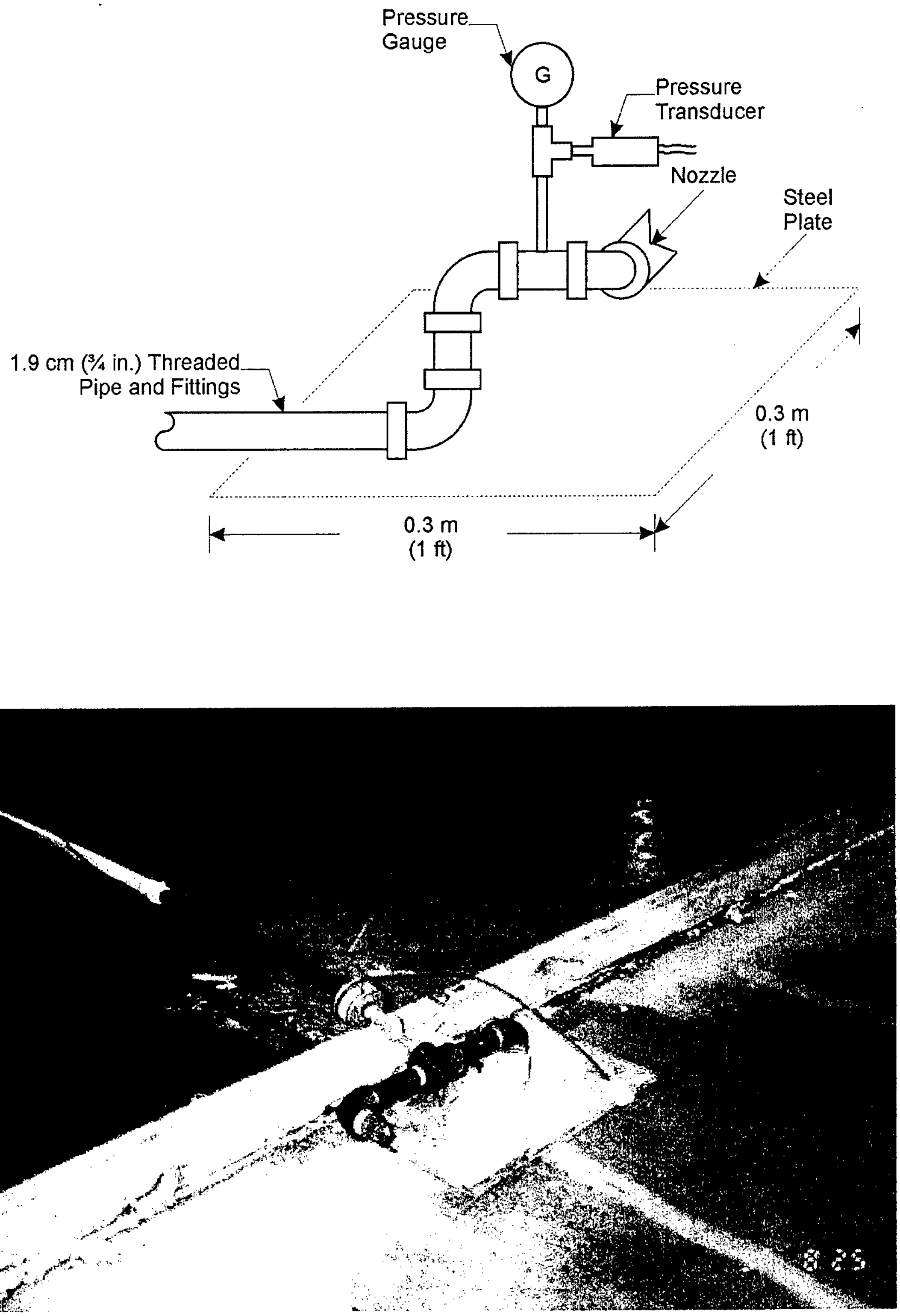


Figure 4 – AFFF nozzle assembly

4.4 Fire Apparatus

The fire apparatus was designed and constructed by the Naval Research Laboratory. The apparatus is shown in Figure 5. The spill fire apparatus consisted of three sections. The first section, the pan, was 1.0 m (3.2 ft) by 0.9 m (3.0 ft) by 15 cm (6 in) deep. The pan is supported by four 0.5 m (1.5 ft) tall steel legs. A 0.5 m (1.5 ft) by 5 cm (2 in) notch was cut on one side of the pan to allow fuel to flow out of the apparatus. A 0.6 m (2.0 ft) by 1.0 m (3.2 ft) steel plate was attached to the pan directly under the notch. The plate extends from the pan to the ground at an angle of 65°.

The second section was the fuel cascade. A 0.9 m (3.0 ft) by 0.6 m (2 ft) by 1.8 m (6 ft) tall steel iron frame constructed of 3.8 cm (1.5 in) angle iron was located inside the pan. This box served as a support for the five cascading trays. The trays were 0.8 m (2.7 ft) by 0.9 m (3.0 ft) wide and are stacked 1.5 m (5.0 ft) high. The trays were bolted to the frame in such a way to allow fuel pumped into the top of the apparatus to flow down each tray and into the test pan below. A square steel roof with 1.2 m (4 ft) sides was attached to the top of the cascade structure to shield the cascade from the sprinkler spray above.

The final section was the fuel delivery piping. The fuel was pumped into the apparatus through 3.8 cm (1.5 in) black steel pipe to various locations on the cascade (top (Fire Scenario 1), middle (Fire Scenario 2), or bottom (Fire Scenario 3)). The fuel cascade and piping was supplied via a 2.5 cm (1.0 in) metal braided flexible hose connected to the bottom of the delivery piping.

The fuel delivery system is shown in Figure 6. The delivery system consisted of two 2200 L (580 gal) fuel storage tanks and a air-driven pump with a capacity of 57 Lpm (15 gpm). The system contained two ball valves, one to control the flow (on or off) and the other to regulate the flow (adjust the fuel flow rate). Between the control valve and the pump was a flow meter to measure the fuel flow rate.

4.5 Instrumentation

Instruments were installed to estimate the size of the fire, the exposure to the structural members of the hangar (primarily temperatures), the exposure to adjacent aircraft (primarily radiation), and the discharge characteristics of the extinguishing systems (pressures and flow rates). The thermocouple grid installed in the ceiling of the building was also used to monitor the conditions produced by the fire. Ambient weather conditions outside the test building were also recorded. The instrumentation scheme for the test area is shown in Figure 7. A complete instrumentation package is found in Appendix A. Measurements from these instruments were recorded every second for the duration of the test. A more detailed description of the instrumentation is listed as follows.

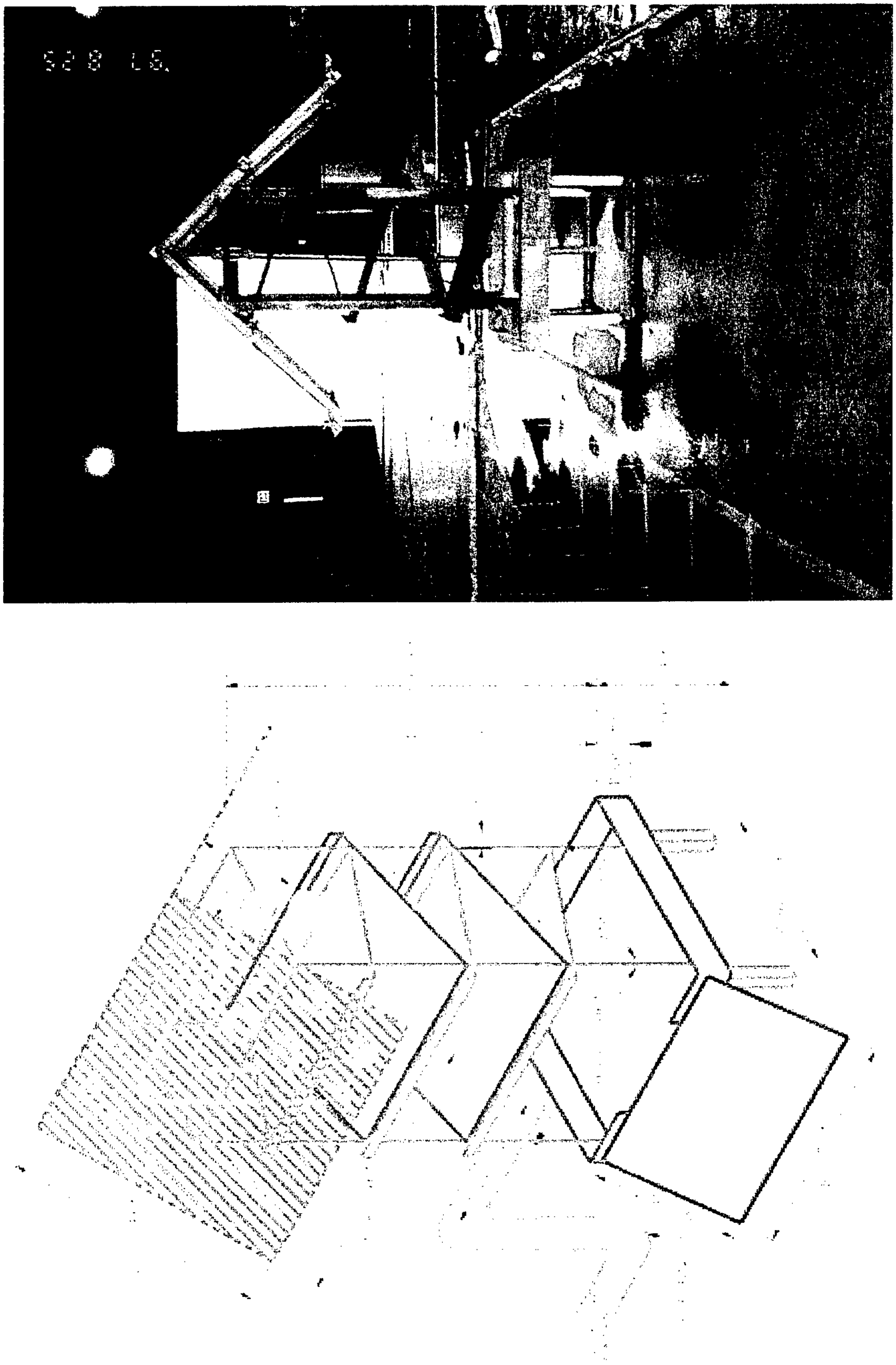


Figure 5 – Spill fire apparatus

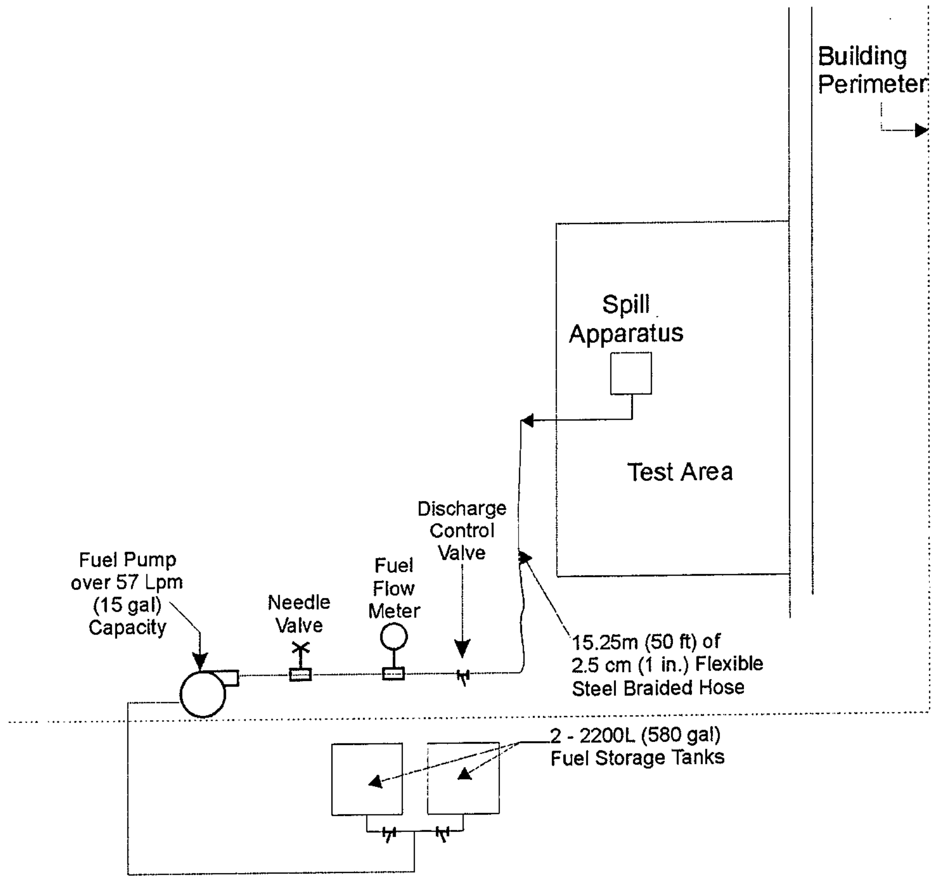


Figure 6 – Fuel delivery system (plan view)

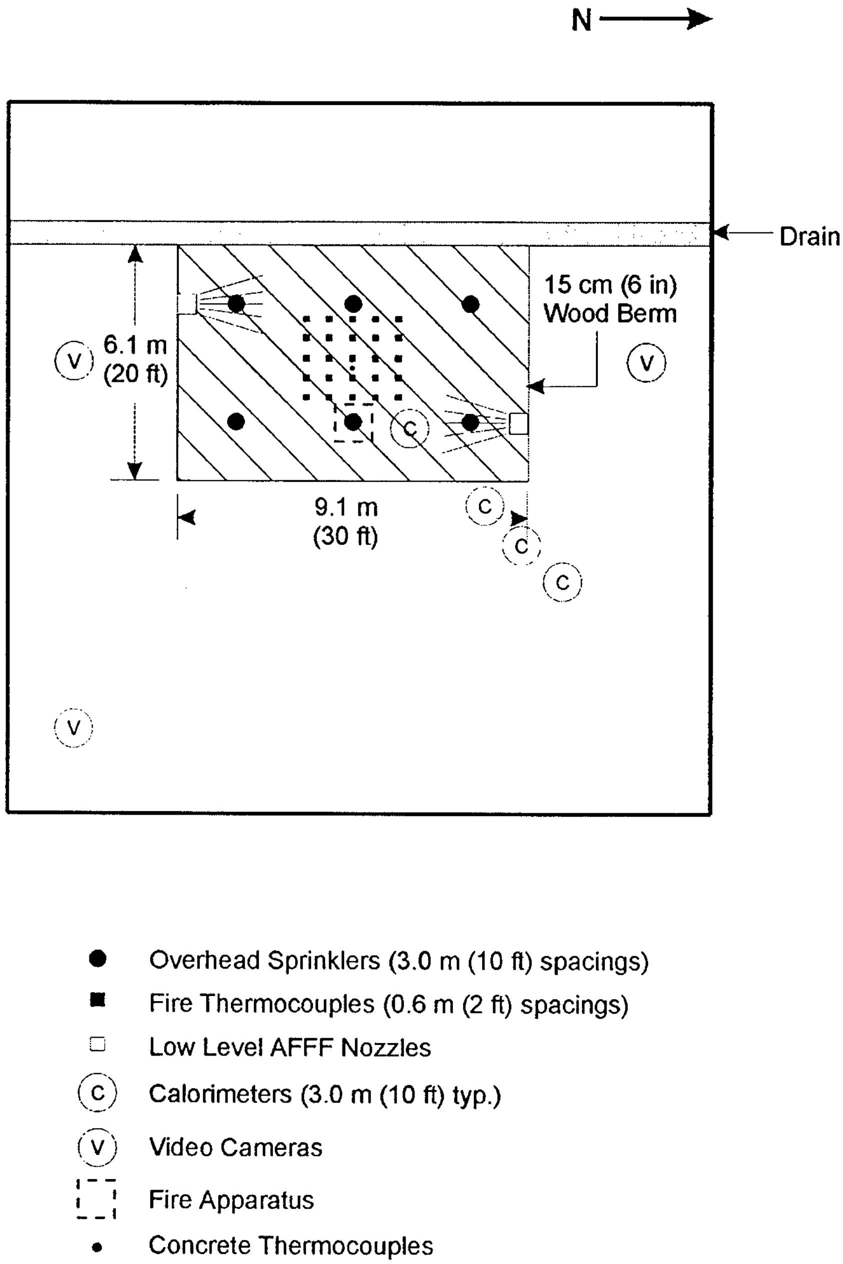


Figure 7 – Instrumentation setup

4.5.1 Thermocouples

Fifty-four thermocouples were installed to measure fire area, ceiling gas temperatures, steel beam temperatures, concrete temperatures and fuel temperatures.

4.5.1.1 Fire Thermocouples

Twenty-five inconel sheathed Type K thermocouples were installed in a five by five matrix in front of the fire apparatus to measure the spread of the fire. These thermocouples were installed with a nominal 0.6 m (2 ft) spacing on the spill side of the fire apparatus. The thermocouples were positioned 0.25 m (10 in) above the deck surface. These thermocouples were fastened to all-thread rod screwed into anchors drilled into the concrete.

4.5.1.2 Steel Beam Thermocouples

Twenty inconel sheathed Type K thermocouples were installed in a steel beam attached to the ceiling directly above the fire apparatus. The thermocouples were installed to measure the surface temperature of the steel beam.

4.5.1.3 Hot Gas Thermocouples

Six inconel sheathed Type K thermocouples were installed in the overhead adjacent to the water sprinklers to measure the hot gas temperatures during the test. The thermocouple grid installed in the ceiling of the building was also used to monitor the conditions produced by the fire.

4.5.1.4 Concrete Thermocouples

Two inconel sheathed Type K thermocouples were used to measure the concrete temperature in the center of the fuel spill. These measurements were made at two depths (flush with the surface and at a depth of 1.25 cm (0.5 in)). The exact location of these thermocouples with respect to the spill apparatus are shown in Figure 7.

4.5.1.5 Fuel Thermocouple

An inconel sheathed Type K thermocouple was also installed in the fuel pan to measure the temperature of the fuel during the test. The thermocouple was located in the center of the pan 2.5 cm (1 in) below the fuel surface.

4.5.2 Calorimeters

Five calorimeters were installed to measure the exposure to adjacent aircraft resulting from the fire. Schmidt Boelter type calorimeters manufactured by Medtherm Company with a full-scale range of 0-50 kW/m^2 were used for this application. Four calorimeters were installed with spacings of 3.0 m (10 ft) radially away in the northeast direction from the center of the fire. The remaining calorimeter were installed 3.0 m (10 ft) away from the center of the fire, 90° from the other calorimeters (west). All five calorimeters were water cooled and installed at an elevation of 0.3 m (1 ft) above the test deck and aimed horizontally.

4.5.3 Flowmeters

Flowmeters were installed in the low level AFFF extinguishing system and the fuel discharge system. Turbine flow meters were used in these applications. The flow meter installed in the Low Level AFFF Extinguishing System had a range of 570 Lpm (150 gpm). The flow meter installed in the Fuel Discharge System had a range of 57 Lpm (15 gpm). The building instrumentation and control system was used to monitor the flow rate of the overhead sprinkler system.

4.5.4 Pressure Transducers

Pressure transducers were installed at both nozzles in the low level AFFF extinguishing system. These transducers were installed to measure the discharge nozzle pressure of the system. The building instrumentation and control system was used to monitor the sprinkler head pressure during each test.

4.5.5 Video

Three video cameras were provided by UL to simultaneously record each test. Two cameras were positioned at the center of two adjacent sides, and the third camera was positioned to give more of an aerial isometric view. Two additional video cameras were provided by the Navy for these tests. The first camera focused on determining the height of the flame during the test, and the second on determining the spill fire area. Both of these cameras were operated by Navy personnel during each test.

4.5.6 Still Photography

Pre-fire and post fire photographs were made of each test as well as continual photographic documentation during the test. The Navy provided additional cameras to document the tests.

4.5.7 Visual Aids

Visual aids were added to aid in the determination of the fire size during the test. These aids consist of a vertical chain positioned at the center of the fuel spill area to aid in the estimation of flame height and a painted grid on the test floor to aid in the estimated of burning surface area.

4.6 Test Procedures

The tests were initiated from the control room located on the east side of the test facility. Upon permission from the Lab Supervisor, the test sequence was initiated. At the start of the test sequence, all personnel assumed their test positions and the pan at the bottom of the fire apparatus was fueled to a depth of 10 cm (4 in). One minute prior to ignition of the fire, the following events occurred: the extinguishing systems were brought on line; both the data acquisition and video equipment were activated, and the accelerant (3.8 L (1.0 gal) heptane)) was added to the fuel pan. The fire was ignited using a torch by a firefighter dressed in protective clothing. After the fire burned for the set period of time (typically one minute), fuel was pumped into the fire apparatus (fuel cascade). The fire then flowed down the cascade and spilled out the ramp producing a spill fire on the floor around the fire apparatus. Once the fire reached the predetermined size (9.3 m^2 (100 ft^2)), the extinguishing system(s) were activated. This typically occurred within two minutes of fuel flow. The test continued for an additional twenty minutes after system discharge or until a spill fire area of 2.3 m^2 (25 ft^2) had reignited (whichever occurred first). Upon completion of the test, the fuel system was secured and firefighters extinguished any remaining fires. The test area remained off limits until cleared by the Test Director and the Safety Officer. Once the test area had been cleared for entering by the Safety Officer, the test area was washed down and cleaned for the next test.

During the tests conducted without AFFF (only water from the overhead sprinklers), the overhead sprinklers were activated simultaneously with the fuel pump. Consequently, water was flowing from the sprinklers prior to the development of the spill fire on the concrete deck. The assumption was made that if the overhead water sprinklers could not stop the fire from growing, the sprinklers would not be able to extinguish the 9.3 m^2 (100 ft^2) spill fire.

5.0 TEST OVERVIEW

The three suppression system parameters that were evaluated during this investigation were: the duration of AFFF discharge, sprinkler application rate and sprinkler activation time. These variables were identified during intermediate scale studies [10]. The effects of these parameters were evaluated against a spill fire scenario produced using either JP-5 or JP-8 aviation fuel. The severity of the spill fire scenario was also varied. A detailed description of these variables is as follows.

Two AFFF discharge durations were evaluated (five and ten minutes). Current AFFF systems are designed to discharge for a duration of ten minutes at the desired application rate. Problems with the concentrate supply or with the proportioning system may result in reduced AFFF flow durations. The five minute AFFF flow duration was chosen to represent the worst-case scenario. In both cases, once the AFFF flow duration was complete, the low level system continued to flow water at the same rate until the end of the test.

Two sprinkler application rates were evaluated during these tests. The first application rate, 6.5 Lpm/m^2 (0.16 gpm/ft^2), is required by NFPA 409 [7] for overhead AFFF sprinklers. The second application rate, 10.2 Lpm/m^2 (0.25 gpm/ft^2), is required by NFPA 13 [8] for Extra Hazard, Group One Occupancies (e.g., airplane hangars).

The overhead water sprinklers were evaluated using two system activations times: simultaneous activation with the AFFF system (simultaneous) and activation at the end of AFFF discharge (delayed). The simultaneous activation represents an overhead deluge application or a rapid response from a closed head sprinkler system (potentially worst-case for the combined system). The delayed activation simulated the time lag associated with a thermally activated sprinkler system. Previous tests [10] have shown variations in system performance related to the time the system was activated.

Typical Navy aircraft fuels include JP-5 (aircraft carrier based fuel) and JP-8 (shore based fuel). These two fuels have different flashpoints (JP-5: 60°C (140°F) and JP-8: 30°C (86°F)) [11] and as identified during the intermediate scale studies, react differently to the combination of AFFF and sprinkler suppression systems. Both fuels were studied in this test series.

The severity of the fire was also varied by changing the location/elevation of the fuel supply to the cascade. The higher the supply elevation, the higher the temperature of the fuel spilling from the fire apparatus. The higher the fuel temperatures spilling from the apparatus, the more severe the fire. Three levels of severity were evaluated during this investigation. Fire Scenario 1 was the most severe and used the full cascade. Fire Scenario 2 was moderately severe and used half of the cascade. Fire Scenario 3 was the least severe and did not use the cascade.

5.1 Test Sequence and Logic – Phase I

The intended Phase I test sequence is shown in the flow chart in Figure 8. Variations in the test sequence were made based on the performance of the system. The first two tests served as a baseline for comparison of the capabilities of a low level AFFF fire suppression system in the absence of overhead sprinklers. These tests were conducted using a five minute AFFF discharge duration which represents a worst-case discharge time (short) for the current low level system designs. Tests three through six evaluated the effects of sprinkler application rate on the low level AFFF fire suppression system for the two test fuels (JP-5 and JP-8). These tests were conducted with the ten minute design AFFF discharge duration. The remaining tests evaluated the effect of AFFF discharge duration and sprinkler activation time. All of the tests in Phase I were conducted using Fire Scenario 1.

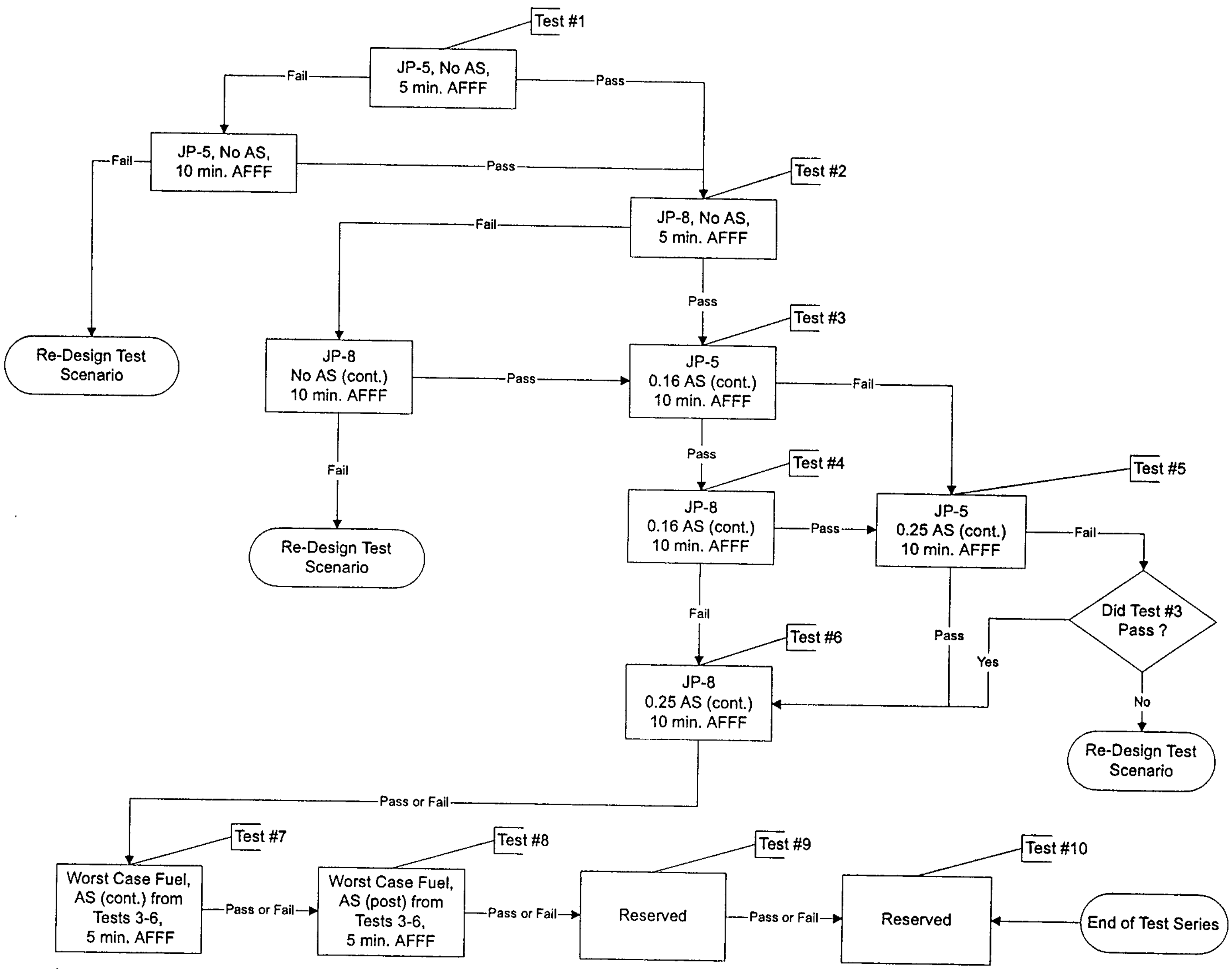


Figure 8 – Test logic flow chart (Phase I)

5.2 Test Sequence and Logic – Phase II

Upon review of the data collected during Phase I of this investigation, it was determined that additional tests were required to further evaluate the proposed aircraft hangar fire protection system. The intended Phase II test sequence is shown in a flow chart in Figure 9. Variations in the test sequence were made based on the results of the tests. The first three tests evaluate the suppression system's capabilities using three sprinkler application rates (0.0, 6.5 and 10.2 Lpm/m^2 (0.0, 0.15 and 0.25 gpm/ft^2)) and a ten minute AFFF discharge duration. These three tests were conducted against the original fire scenario (Fire Scenario 1). This scenario was considered a "worst-case" fire scenario due to the heating of the fuel in the cascade. The next set of tests (Tests 4-8) evaluate both the proposed system as well as a water only overhead sprinkler system against a less severe threat (Fire Scenario 3). The less severe fire scenario was produced by effectively removing the fuel cascade. If the water only overhead sprinkler system would have produced acceptable results, the water only system would have been re-evaluated against the original "worst-case" fire scenario as well as evaluated using closed heads. Since this was not the case, the water only overhead sprinkler system was re-evaluated using higher water application rates.

6.0 RESULTS

The investigation included twenty-three full-scale fire tests and was conducted in two phases. The first phase of testing was conducted using both JP-5 and JP-8 test fuels and focused primarily on evaluating the effect that overhead sprinklers have on the capabilities of a low level AFFF fire suppression system for a worst-case fire scenario. During the initial phase of testing, questions arose pertaining to both the severity of the fire (i.e., unrealistically severe due to the heating of the fuel to it's boiling point prior to spilling on the deck) and to the quantity of fuel spilling from the fire apparatus (i.e., the heating of the fuel increased the amount of fuel burned in the fire apparatus and reduced the amount of fuel spilled on the deck). The flashpoint of the JP-8 test fuel was also determined to be approximately 10°C (18°F) higher than the JP-8 found on typical Navy installations. Due to the questions pertaining to the fires and the fuels, the second phase of tests was required.

The second phase of full-scale tests were conducted using a lower flashpoint JP-8 test fuel (flashpoint of 47°C (117°F)). These tests were used to re-evaluate the effects of overhead sprinklers on the low level AFFF fire suppression system against fuel spill fire scenarios with varying degrees of severity. Both phases of testing also included an evaluation of the capabilities of an overhead water only sprinkler system.

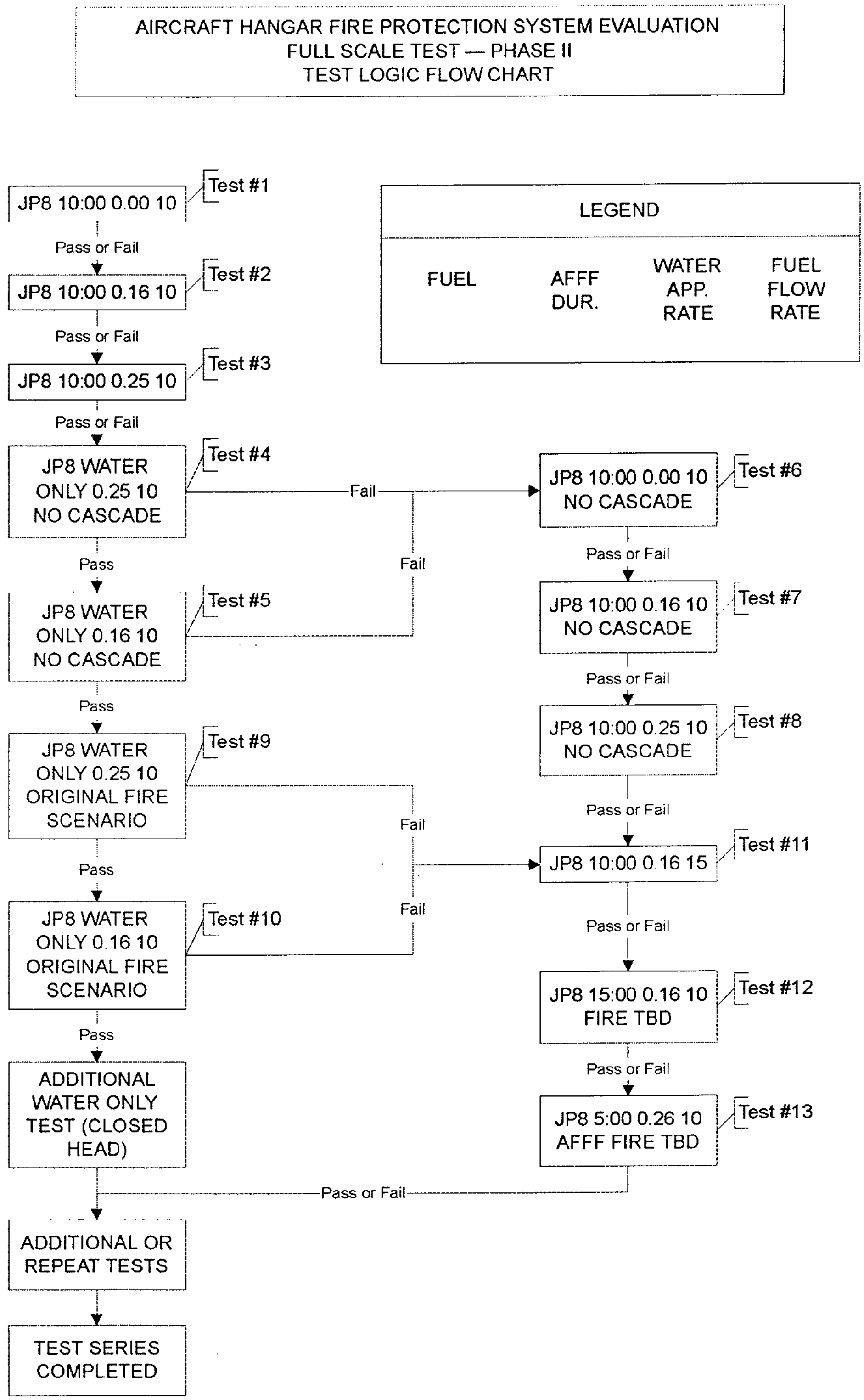


Figure 9 – Test logic flow chart (Phase II)

The results of the tests conducted during Phase I and Phase II of this investigation are shown in Tables 1 and 2 respectively. A complete data package for each test is found in Appendix A.

The first eight rows in the tables provided information describing the conditions of the test. The next seven rows described the worst-case conditions produced by the fire. The spill fire size/area was determined using the temperature grid located in front of the fire apparatus, and on visual observations conducted during the test. The flame height was the height of the continuous flame as determined by visual observations. These two measurements (spill area and flame height) were then used to estimate the heat release rate of the fire. These estimated heat release rates were in agreement with what would be expected if all of the fuel supplied to the apparatus was being consumed (based on the fuel flow rate and the heat of combustion of the fuel). Also shown in the tables were the exposures to adjacent aircraft (radiant heat fluxes) as measured at various distances away from the fire. The effect of the application of water on the AFFF foam blanket was based on both fire suppression and burnback resistance. The extinguishment times were based primarily on visual observations. The 90% extinguishment time was the time to extinguish 90% of the spill fire. The 100% extinguishment time was the time when all visual flames were extinguished. The burnback times for Fire Scenario 1 were based on both the measurements from the thermocouple grid installed in front of the fire apparatus and on visual observations. The burnback times for Fire Scenarios 2 and 3 were based primarily on visual observations. These burnback times were defined as the time from the end of AFFF discharge to the time the spill fire began to burn out of control. This typically corresponded to a spill fire area of approximately 3 m^2 (30 ft^2).

6.1 Fire Scenarios

Two test fuels were included in this evaluation (JP-5 and JP-8). During the initial week of testing (Phase I), the flashpoints of the test fuels were measured to be 63°C (146°F) for the JP-5 and 54°C (130°F) for the JP-8 [12]. The flashpoint of the JP-5 was representative of that found in typical Navy installations but the flashpoint of the JP-8 was 10°C (18°F) higher than expected. During the second phase of the testing (Phase II), tests were conducted using only JP-8 with a measured flashpoint of 47°C (117°F).

Three fire scenarios were included in this evaluation. These scenarios consisted of: Fire Scenario 1 – a full cascade with a 38 Lpm (10 gpm) fuel flow rate, Fire Scenario 2 – a half cascade with a 57 Lpm (15 gpm) fuel flow rate and Fire Scenario 3 – no cascade with a 38 Lpm (10 gpm) flow rate. An analysis of these fire scenarios is found in Appendix B. The results of this analysis are shown in Figure 10 and are discussed in subsequent sections of this report.

6.1.1 Fire Scenario 1: Full Cascade/38 Lpm (10 gpm) Fuel Flow Rate

Fire Scenario 1 consisted of 38 Lpm (10 gpm) of fuel pumped into the top of the fuel cascade (five ramps). This scenario produced the most severe conditions of the three fire

Table 1. Aircraft Hangar Suppression System Evaluation - Phase I Summary Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Fuel	JP8	JP5	JP5	JP8	JP8	JP5	JP8	JP8	JP8	JP8	JP5	JP8
Fire Scenario	1	1	1	1	1	1	1	1	1	1	1	1
Fuel Flow Rate, Lpm (gpm)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)
Fire Scenario - Cascade	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full
AFFF Duration (min)	5:00	5:00	10:00	10:00	10:00	10:00	5:00	5:00	10:00	5:00	N/A	10:00
Sprinkler Application Rate, Lpm/m^2 (gpm/ft^2)	0.0 (0.0)	0.0 (0.0)	6.5 (0.16)	6.5 (0.16)	10.2 (0.25)	10.2 (0.25)	6.5 (0.16)	6.5 (0.16)	6.5 (0.16)	6.5 (0.16)	10.2 (0.25)	0.0 (0.0)
Sprinkler Actuation Time	N/A	N/A	SIM	SIM	SIM	SIM	SIM	SIM	SIM	DELAYED	ONLY	N/A
Fuel Spill Area, m^2 (ft^2)	7.6 (82)	6.7 (72)	7.4 (80)	8.0 (86)	8.9 (96)	8.2 (88)	7.6 (82)	7.8 (84)	7.6 (82)	8.0 (86)	7.6 (82)	7.8 (84)
Fuel Temperature, °C (°F)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)
Concrete Temperature, °C (°F) depth = 1.25 cm (0.5 in)	27 (80)	32 (90)	29 (85)	27 (80)	32 (90)	32 (90)	35 (95)	29 (85)	32 (90)	32 (90)	29 (85)	32 (90)
Flame Height at Actuation, m (ft)	12.2 (40)	12.2 (40)	12.2 (40)	10.7 (35)	9.2 (30)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)
Est. Heat Release Rate, MW	21	19	22	22	23	22	21	21	21	22	21	21
Ceiling Temperature, °C (°F)	200 (392)	200 (392)	220 (428)	220 (428)	200 (392)	190 (374)	210 (410)	210 (410)	190 (374)	210 (410)	210 (410)	210 (410)
Heat Flux at Actuation, kW/m^2												
3.0 m (10 ft)	45.0	38.0	30.0	50.0	32.0	31.0	33.0	31.0	25.0	31.0	47.0	28.0
6.1 m (20 ft)	15.5	13.0	10.0	22.0	10.0	12.0	11.0	12.0	9.0	10.0	12.0	9.0
9.1 m (30 ft)	7.0	5.5	4.0	12.0	5.0	5.5	6.0	7.0	6.0	5.0	6.5	5.0
12.2 m (40 ft)	5.0	4.0	2.5	8.0	3.5	4.0	4.0	5.0	4.0	3.0	4.5	3.5
90% Extinguishment Time (s)	40	35	16	29	25	22	17	14	17	17	No	23
100% Extinguishment Time (s)	45	50	25	45	45	27	23	30	32	47	No	34
Burnback Time (min) (After AFFF Discharge)	6:00	5:00	7:00	5:00	7:00	5:00	3:00	3:00	6:00	4:00	N/A	6:00

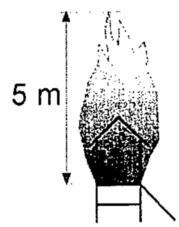
SIM - The sprinkler system and low level AFFF system were activated simultaneously.
DELAYED - The sprinkler activation was delayed until after the fire was extinguished.
N/A - The sprinklers were not activated during the test.
ONLY - The test was conducted with only the overhead sprinklers.

Table 2. Aircraft Hangar Suppression System Evaluation - Phase II Summary Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11
Fuel	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8
Fire Scenario	1	1	3	3	3	3	2	2	2	2	2
Fuel Flow Rate, Lpm (gpm)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	57 (15)	57 (15)	57 (15)	57 (15)	57 (15)
Fire Scenario - Cascade	Full	Full	No	No	No	No	½	½	½	½	½
AFFF Duration (min)	10:00	10:00	N/A	10:00	10:00	10:00	10:00	10:00	10:00	N/A	N/A
Sprinkler Application Rate, Lpm/m² (gpm/ft²)	0.0 (0.0)	6.5 (0.16)	10.2 (0.25)	0.0 (0.0)	10.2 (0.25)	6.5 (0.16)	6.5 (0.16)	10.2 (0.25)	0.0 (0.0)	20.4 (0.5)	40.8 (1.0)
Sprinkler Actuation Time	N/A	SIM	SIM	N/A	SIM	SIM	SIM	SIM	N/A	ONLY	ONLY
Fuel Spill Area, m² (ft²)	8.8 (95)	8.4 (90)	7.9 (85)	7.9 (85)	7.9 (85)	7.9 (85)	8.4 (90)	8.4 (90)	7.9 (85)	N/A	N/A
Fuel Temperature, °C (°F)	200 (400)	200 (400)	43 (110)	32 (90)	38 (100)	35 (95)	91 (195)	91 (195)	93 (200)	77 (170)	82 (180)
Concrete Temperature, °C (°F) depth = 1.25 cm (0.5 in)	22 (71)	19 (66)	20 (68)	16 (60)	9 (48)	11 (51)	9 (48)	25 (77)	25 (77)	29 (85)	28 (71)
Flame Height at Actuation, m (ft)	9.8 (32)	9.8 (32)	9.2 (30)	9.8 (32)	9.2 (30)	9.2 (30)	10.7 (35)	9.2 (30)	9.2 (30)	N/A	N/A
Est. Heat Release Rate, MW	23	22	21	22	21	21	24	22	21	N/A	N/A
Ceiling Temperature, °C (°F)	200 (392)	190 (374)	120 (248)	25 (77)	20 (68)	22 (72)	30 (86)	25 (77)	40 (104)	35 (95)	30 (86)
Heat Flux at Actuation, kW/m²											
3.0 m (10 ft)	36.0	30.0	N/A	30.0	33.0	31.0	38.0	29.0	36.0	N/A	N/A
6.1 m (20 ft)	10.0	12.0		9.0	9.0	9.0	11.0	9.5	11.0		
9.1 m (30 ft)	7.0	6.0		4.0	4.0	4.0	5.0	4.5	5.0		
12.2 m (40 ft)	3.0	4.0		2.0	2.0	2.0	2.5	2.5	2.5		
90% Extinguishment Time (s)	23	30	No	25	47	36	39	37	41	No	No
100% Extinguishment Time (s)	39	82	No	57	70	49	54	53	60	No	No
Burnback Time (min) (After AFFF Discharge)	4:00	5:00	N/A	13:00	4:00	4:00	4:00	3:00	5:00	N/A	N/A

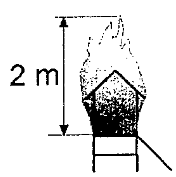
SIM - The sprinkler system and low level AFFF system were activated simultaneously.
DELAYED - The sprinkler activation was delayed until after the fire was extinguished.
N/A - The sprinklers were not activated during the test.
ONLY - The test was conducted with only the overhead sprinklers.

Fire Scenario 1
Full Cascade



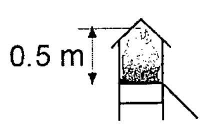
38 Lpm (10 gpm) Fuel Flow Rate
19 Lpm (5 gpm) Cascade
19 Lpm (5 gpm) Fuel Spill 5 m^2 (50 ft^2)
200 °C (400 °F) Fuel Spill Temperature
70 Kw/m^2 Exposure at Base of Ramp

Fire Scenario 2
1/2 Cascade



57 Lpm (15 gpm) Fuel Flow Rate
7.6 Lpm (2 gpm) Cascade
49.4 Lpm (13 gpm) Fuel Spill
95 °C (200 °F) Fuel Spill Temperature
28 Kw/m^2 Exposure at Base of Ramp

Fire Scenario 3
No Cascade



38 Lpm (10 gpm) Fuel Flow Rate
1.9 Lpm (0.5 gpm) Cascade
36.1 Lpm (9.5 gpm) Fuel Spill
38 °C (100 °F) Fuel Spill Temperature
7 Kw/m^2 Exposure at Base of Ramp

Figure 10 – Fire scenarios

scenarios included in this evaluation. Once the fire apparatus reached steady-state conditions (~ 3:00 into the test), it was estimated that half of the fuel (19 Lpm (5 gpm)) was burned in the cascade and the other half spilled down the ramp onto the deck. The 19 Lpm (5 gpm) burned in the cascade produced approximately a 10 MW fire which heated the fuel to approximately 200°C (400°F) and provide a radiant exposure of over 70 kW/m^2 at the base of the fire apparatus (ramp). This boiling fuel and radiant flux provided a significant challenge to the extinguishing system(s) with respect to both extinguishment and burnback. The 19 Lpm (5 gpm) of boiling fuel spilling down the ramp was capable of producing a steady-state spill fire on the order of 5 m^2 (50 ft^2). Since steady-state conditions are not reached simultaneously, the initial spill fire prior to system activation was typically larger than the steady-state value. The combination of the radiation from the fire apparatus and the spilling of boiling fuel provided a significant insult to the AFFF foam blanket at the base of the ramp. As a result, the fire became established at the base of the ramp shortly after the end of AFFF discharge (the switch from AFFF solution to water).

6.1.2 Fire Scenario 2: Half Cascade/57 Lpm (15 gpm) Fuel Flow Rate

Fire Scenario 2 consisted of a half cascade (three ramps) and was conducted with a fuel flow rate of 57 Lpm (15 gpm). This scenario produced moderately severe (relative to the other scenarios) conditions. It was estimated, based on the radiation and the flame height measurements, that approximately 7.6 Lpm (2 gpm) of fuel was burned in the cascade and that 49.4 Lpm (13 gpm) of fuel was spilled down the ramp onto the deck. The 7.6 Lpm (2 gpm) burned in the cascade produced approximately a 5 MW fire which heated the fuel to 94°C (~200°F) and provided a radiant exposure of over 28 kW/m^2 at the base of the fire apparatus (ramp). This heated fuel and radiant flux provided a less severe exposure to the foam blanket than Fire Scenario 1. The remaining 49.4 Lpm (13 gpm) spilling down the ramp was capable of producing a steady-state spill fire on the order of 12 m^2 (130 ft^2). During Fire Scenario 2, the suppression systems were activated when the spill fire area reached 9.3 m^2 (100 ft^2). The suppression systems were capable of quickly extinguishing the fire and prevented burnback until the foam blanket was washed away by the water being discharged by both the low level and overhead systems.

6.1.3 Fire Scenario 3: No Cascade/38 Lpm (10 gpm) Fuel Flow Rate

The scenario consisted of 38 Lpm (10 gpm) of fuel pumped into the bottom of the fuel cascade (1/2 ramp). Fire Scenario 3 was the least severe of the three scenarios. It was estimated based on the radiation and flame height measurements, that approximately 1.9 Lpm (0.5 gpm) burned in the fire apparatus (pan at the bottom of the cascade) and 36.1 Lpm (9.5 gpm) of fuel was spilled down the ramp onto the deck. The 1.9 Lpm (0.5 gpm) burned in the apparatus produced approximately a 1 MW fire which heated the fuel to 38°C (~100°F) and produced a radiant exposure of over 7 kW/m^2 at the base of the fire apparatus (ramp). The 36.1 Lpm (9.5 gpm) of fuel spilling down the ramp was capable of producing a steady-state spill fire on the order of 9.3 m^2 (100 ft^2). This fire was typically quickly extinguished and did not reignite (burnback) until the AFFF foam blanket had been washed away by the water being discharged from the low level and overhead systems.

6.2 The Effect of Water Sprinklers on Low Level AFFF Fire Suppression Systems

The use of overhead water sprinklers had only a minimal effect on the ability of the low level AFFF fire suppression system to extinguish a fire but had varying effects on the ability of the system to resist burnback.

6.2.1 The Effect of Water Sprinklers on Fire Suppression and Extinguishment

Throughout this test series the fires were typically controlled (90% extinguished) in approximately 30 seconds with complete extinguishment occurring approximately 30 seconds later. The control (90% extinguishment) and extinguishment times are shown in Figures 11 and 12 for the tests conducted with JP-8.

As shown in Figure 11, the application of water from the overhead sprinklers had random effects on the control times (90% extinguishment time). For Fire Scenario 3, increasing the application rate systematically increased the 90% extinguishment times. For Fire Scenario 2, increasing the application rate systematically decreased the 90% extinguishment times. For Fire Scenario, 1, the application of water produced random results.

The same variability was observed for the 100% extinguishment times. As shown in Figure 12, increasing the application rate systematically reduced the extinguishment times for Fire Scenario 2 but produced random results for Fire Scenarios 1 and 3.

Independent of the fire scenario and sprinkler application rate, the AFFF foam blanket spread across the surface of the test area extinguishing the fire at the base of the fire apparatus resulting in only small pockets of isolated fires around the perimeter of the test area. These small isolated fires typically remained burning until the foam blanket covered the entire test area (approximately one minute after AFFF system activation). The duration of these isolated fires appeared random in nature but the movement was a function of the spray patterns of the low level nozzles and the resulting solution flow across the test area. This flow dependency produced similar results between tests independent of fire scenario, fuel type and sprinkler application rate. A typical extinguishment history is shown in Figure 13. Consequently, it can be concluded that the discharge from the overhead sprinklers had little if any effect on the extinguishment capabilities of the low level AFFF fire suppression system.

An Analysis of Variance (ANOVA) was also conducted on the data to verify these conclusions. A detailed description of this analysis is found in Appendix C. The analysis defines the probability that two sets of data are similar for a given confidence level. A 90% confidence level was used in this analysis. If the probability determined using this analysis is

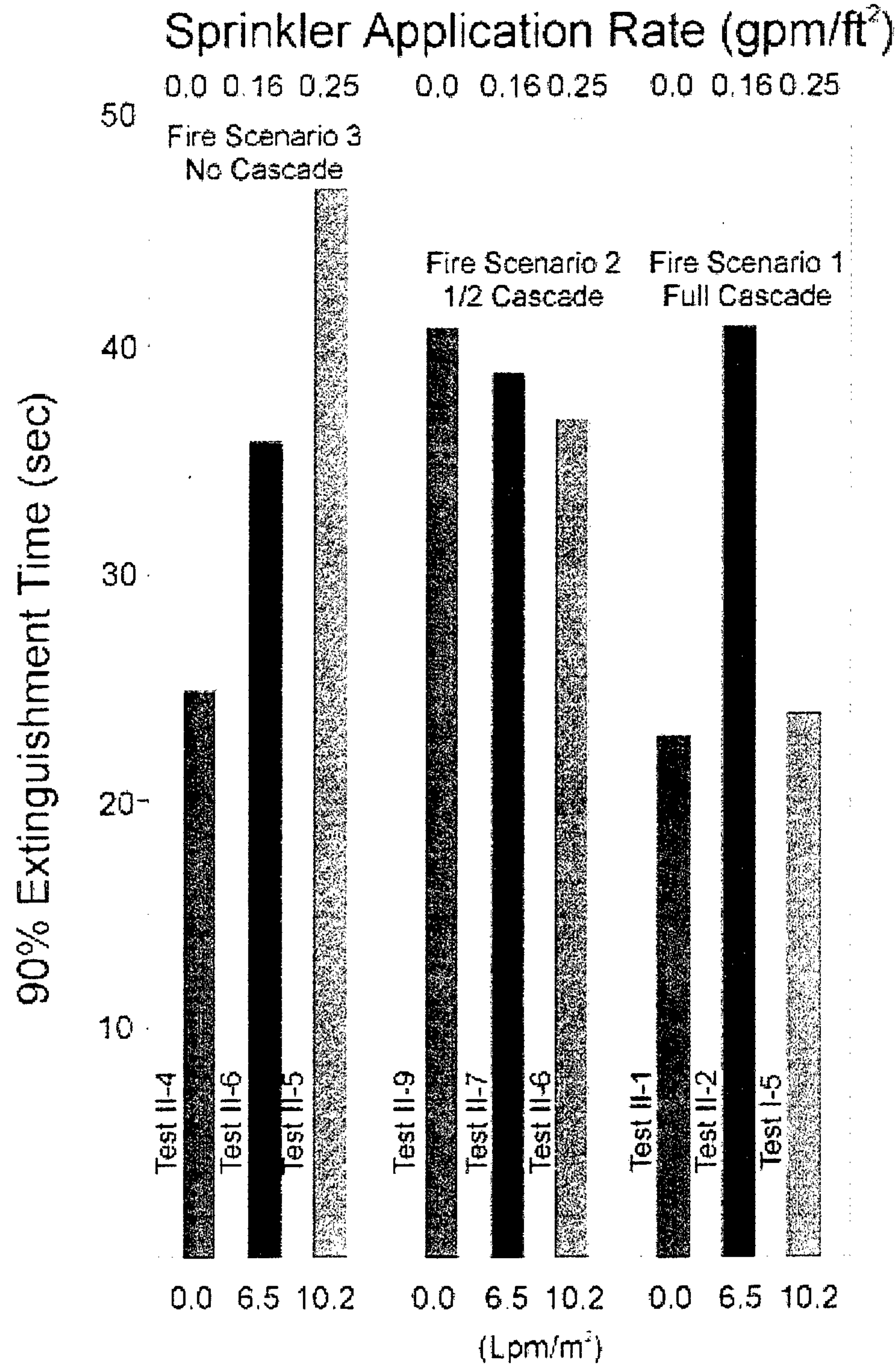


Figure 11 – Spill fire control times

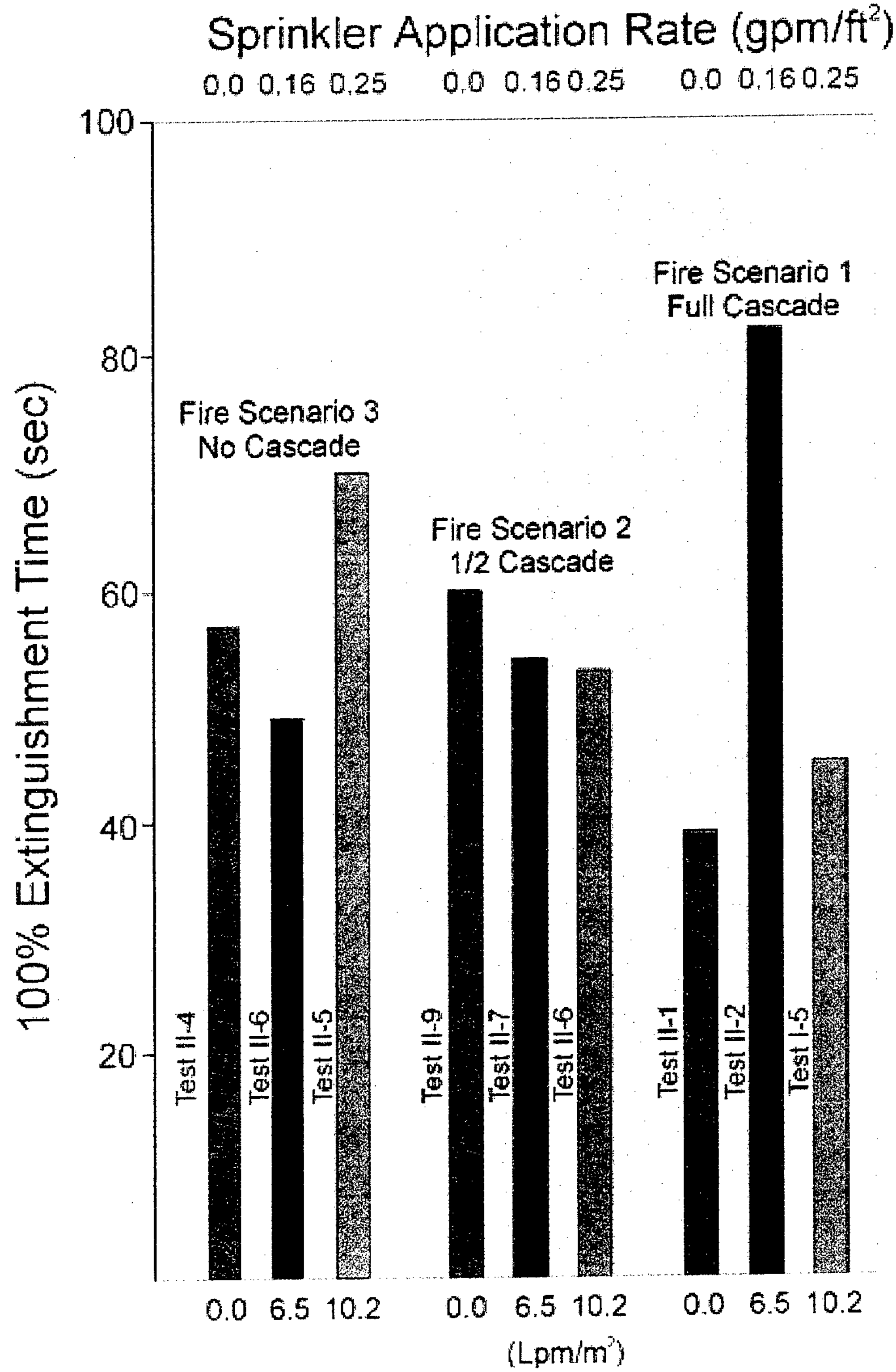


Figure 12 – Spill fire extinguishment times

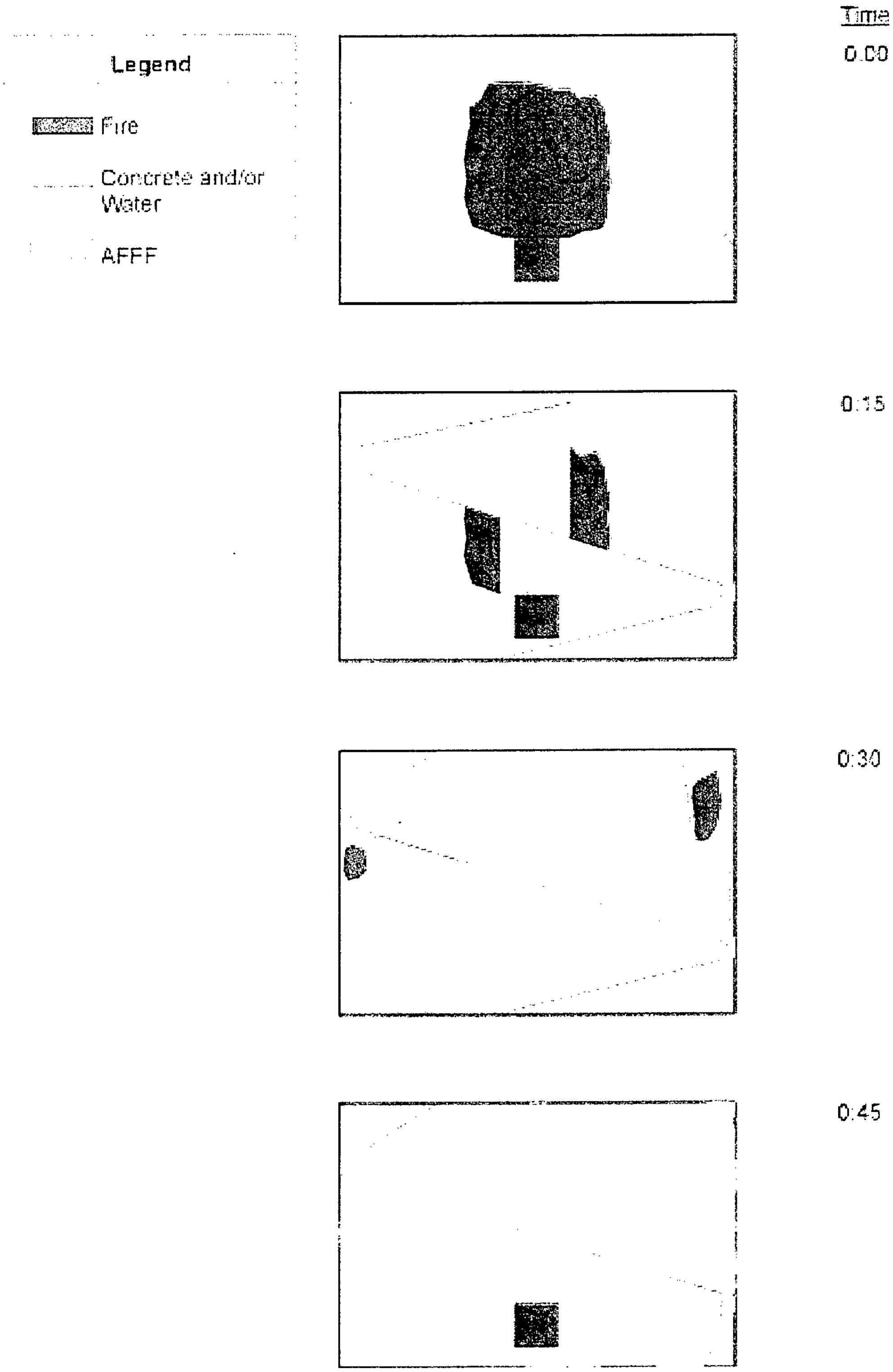


Figure 13 – Typical extinguishment history

less than 0.1, the two sets of data are statistically different. If the probability is greater than 0.1, the two sets of data are statistically similar.

The analysis was conducted on the 90% and 100% extinguishment times for the three sprinkler application rates evaluated during this investigation (0.0, 6.5 and 10.2 Lpm/m^2 (0.0, 0.16 and 0.25 gpm/ft^2)). The probability determined for the 90% and 100% extinguishment times were 0.25 and 0.84 respectively suggesting that the results were statistically similar between the tests conducted with the various application rates. In conclusion, the water sprinklers had little effect on the fire suppression and extinguishment capabilities of the system.

6.2.2 The Effect of Water Sprinklers on Burnback Resistance

Throughout this test series, burnback typically occurred three to five minutes after the end of AFFF discharge (the switch from AFFF to water). Once the AFFF foam blanket drained away, the fire quickly became established in the area directly in front of the fire apparatus. The flow of the solution (AFFF, fuel and water) around the test area appeared to be the primary variable relating to fire spread. Typically, the fire would flow toward the west edge of the test area and then move slowly down the boundary toward the drain. Once the fire reached the AFFF nozzle (which was now discharging water), the fire would quickly spread back across the test area and the test would be terminated. A typical burnback sequence is shown in Figure 14.

The burnback time appeared to be unaffected by overhead sprinkler application rate (in the range of application rates evaluated during this test series). As shown in Figure 15, the discharge of water from the overhead sprinklers reduced the burnback times by over one minute for Fire Scenario 2, but increased the burnback resistance by over two minutes for Fire Scenario 1. A direct comparison for Fire Scenario 3 is not appropriate due to drainage obstructions that occurred during the test. Independent of the sprinkler application rate, the burnback protection provided by the system to the hangar is lost shortly after the end of AFFF discharge and appears to be primarily a function of the drainage characteristics of the hangar. A conservative interpretation of these results would assume that burnback protection for the hangar is only provided during the discharge of AFFF.

The ANOVA technique was also used to evaluate the effects that the various sprinkler application rates had on the ability of the system/foam blanket to resist burnback. The analysis was conducted for the three application rates evaluated during this investigation (0.0, 6.5 and 10.2 Lpm/m^2 (0.0, 0.16 and 0.25 gpm/ft^2)). The probability determined for the burnback data was 0.68 suggesting that the results were statistically similar between the various application rates. In conclusion, the sprinklers had little effect on the ability of the system/foam blanket to resist burnback.

The results collected during both the intermediate- and full-scale test series suggest that the primary variable associated with burnback may be the slope of the hangar floor and resulting drainage. The results of these tests suggest that the steeper the slope of the floor, the faster the AFFF would drain away. One could argue that poor drainage due to a somewhat level floor or a

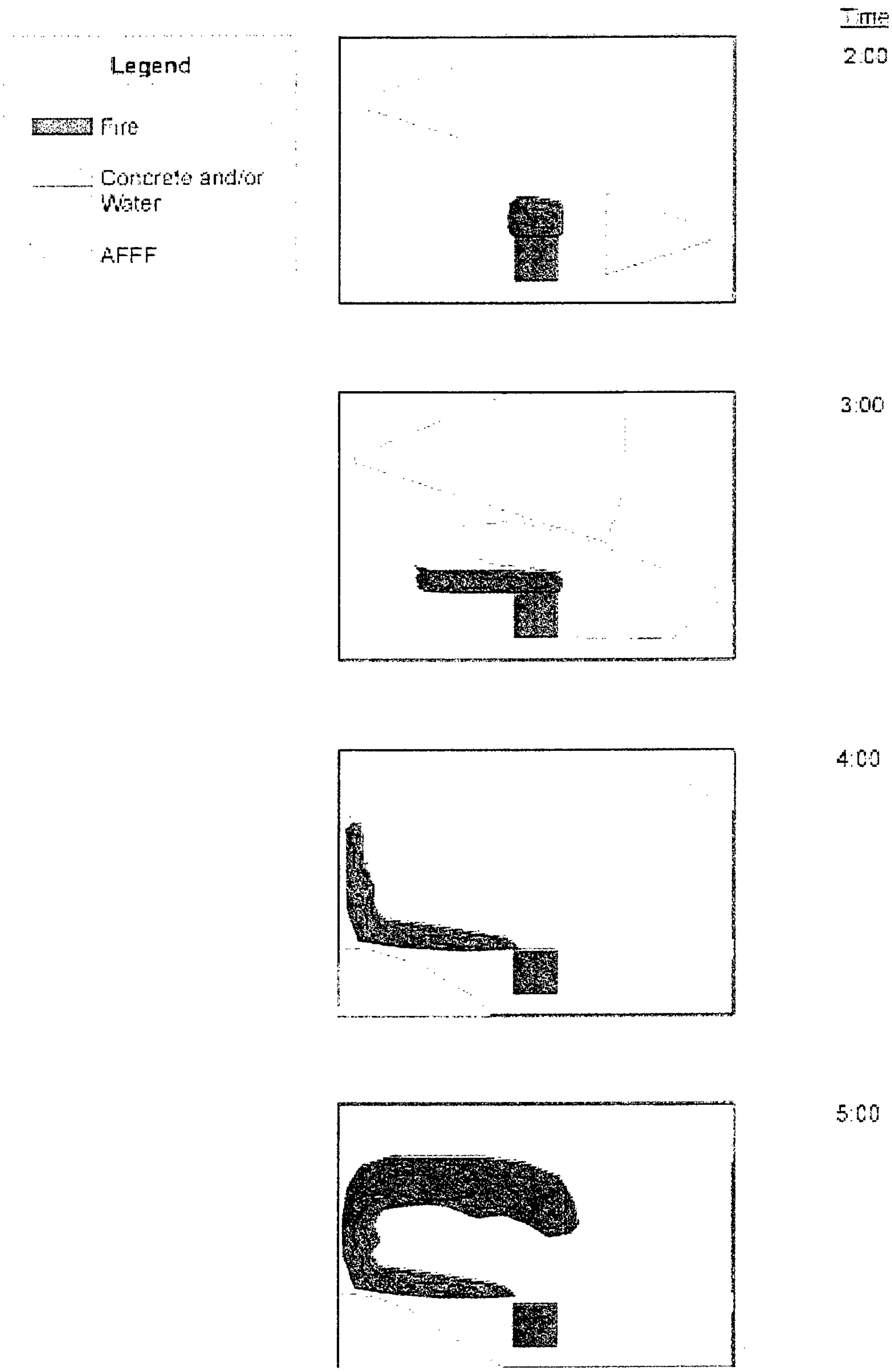


Figure 14 – Typical burnback history

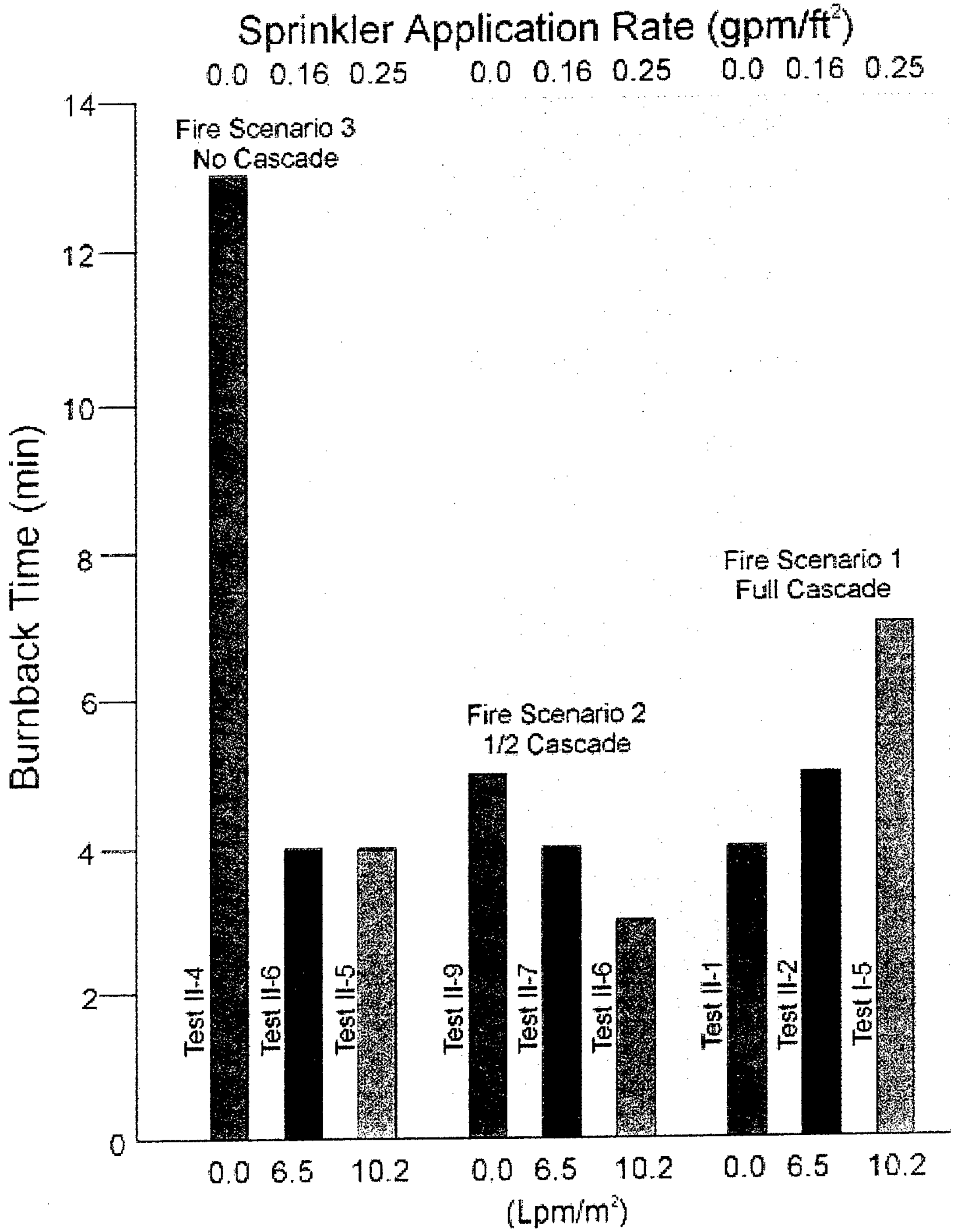


Figure 15 – Spill fire burnback times

stagnent flow pattern created by the low level system, would increase the burnback protection. This is supported by the results of the tests conducted with Fire Scenario 3 (no cascade/38 Lpm (10 gpm) fuel flow rate). During the baseline test conducted without overhead sprinkler application (Phase II - Test 4), the AFFF foam blanket provided thirteen minutes of protection after the AFFF concentrate was consumed. This anomaly in the data was in part the result of poor drainage in the test area during the test. The poor drainage was the result of a flow obstruction created by instrument wires running across the test area that were accidently laid on the concrete slab rather than elevated as during previous tests. These instrument wires channeled the water flow away from the fire apparatus allowing the foam blanket at the base of the apparatus to remain intact longer than during previous tests. It is believed that if this barracade was not present, the burnback results would have been similar to the other tests (4-5 min).

6.3 Fuel Type Comparison

Throughout this test series there were minor variations in the fire suppression capabilities of the system(s) for the two test fuels (JP-5 and JP-8). As shown in Figure 16, the JP-8 fires were controlled in less than 30 seconds, and the JP-5 fires controlled in less than 20 seconds. The JP-8 fires were extinguished in approximately 60 seconds and the JP-5 fires were extinguished in less than 30 seconds. The plots on Figure 16 show definite trends in the data with the lower flashpoint fuels being more difficult to control and extinguish than the higher flashpoint fuels.

Burnback resistance showed the greatest variations between the test fuels. As shown in Figure 17, the lower flashpoint fuels burned back quicker than the higher flashpoint fuels. For the test scenario shown in Figure 17 (Fire Scenario 1 – 6.5 Lpm/m^2 (0.16 gpm/ft^2) sprinkler application rate), burnback occurred for the JP-5 seven minutes after the end of AFFF discharge as compared to only four minutes for JP-8. Although the burnback times for the lower flashpoint fuels were faster than the higher flashpoint fuels, the duration of protection was not significantly altered. In summary, these tests show that overhead water sprinklers (with application rates up to 10.2 Lpm/m^2 (0.25 gpm/ft^2)) have minimal effect on AFFF foam blankets, independent of the test fuel, fire scenario and sprinkler application rate. The tests show that a combined low level AFFF extinguishing system operating in conjunction with an overhead water sprinkler system will provide adequate protection for the hangar during AFFF discharge but the protection in terms of burnback resistance, may be lost shortly (a few minutes) after the end of AFFF discharge.

The ANOVA technique was also used to evaluate how the test results varied as a function of fuel type. The analysis was conducted on both the extinguishment and burnback times recorded during this investigation. The technique was used to compare the results of the JP-5 tests conducted during Phase I to the JP-8 tests conducted during Phase II.

When analyzing the extinguishment times, the technique produced a probability of 0.005 suggesting that the 90% extinguishment times were different for the two test fuels. The times for

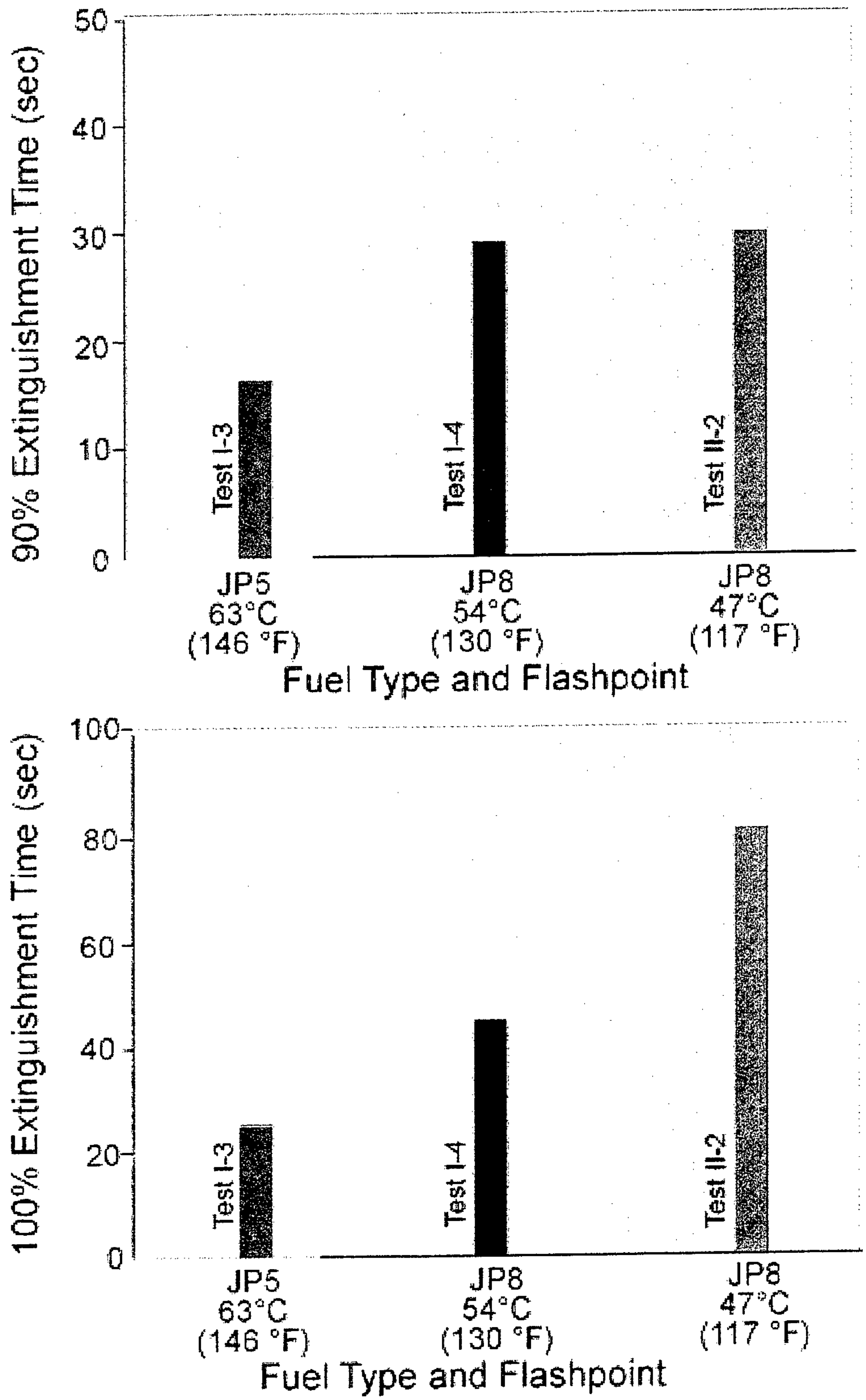


Figure 16 – Fuel type comparison - fire suppression capabilities

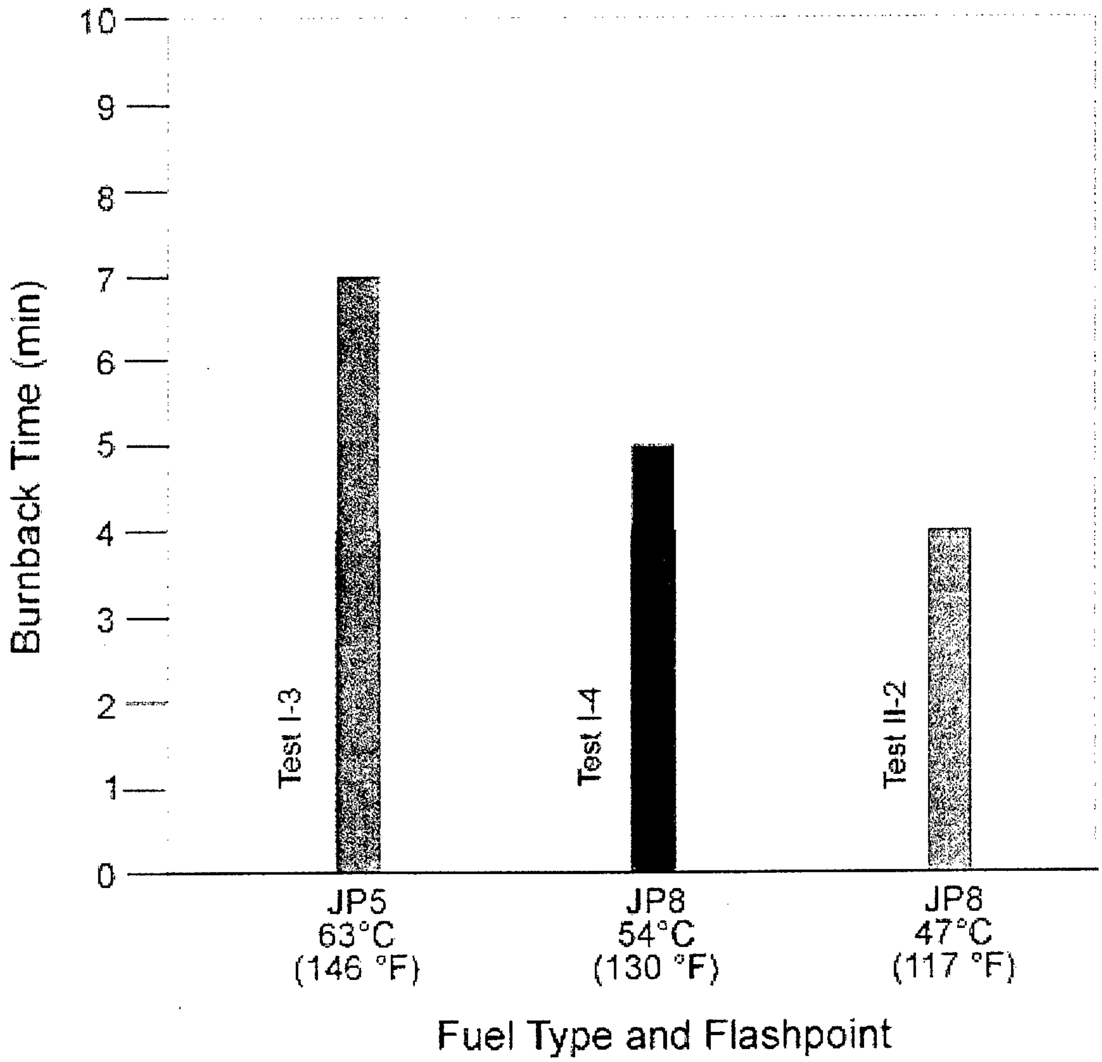


Figure 17 – Fuel type comparison - burnback resistance

complete extinguishment followed the same trends with a probability of 0.006 suggesting that the 100% extinguishment times were also different.

When analyzing the burnback times, the technique produced a probability of 0.053 suggesting that the burnback times were different between the two fuels with the lower flashpoint fuel (JP-8) producing statistically faster burnback times. In conclusion, the lower flashpoint fuels take longer to control (90% extinguishment) and extinguish (100% extinguishment) and burnback faster than the higher flashpoint fuels.

6.4 The Fire Suppression Capabilities of an Overhead Water Only Sprinkler System

Four tests were conducted to evaluate the fire suppression capabilities of an overhead water-only sprinkler system. The tests were conducted using three sprinkler application rates 10.2, 20.4 and 40.8 Lpm/m^2 (0.25, 0.5 and 1.0 gpm/ft^2). The lowest application rate was evaluated against both Fire Scenarios 1 and 3. The higher application rates were evaluated against Fire Scenario 2.

During this evaluation, the overhead sprinklers were activated prior to the development of the spill fire on the concrete deck. This early activation provided an advantage to the sprinkler system by not allowing the fire and fire effects (i.e., hot layer and plume velocities) to initially effect the spray characteristics (i.e., droplet sizes and velocities) of the sprinklers. It was assumed that if the fire grew relatively unabated, the system would not have been able to extinguish the fire using a delayed activation.

During the three tests conducted with a sprinkler application rate of 20.4 Lpm/m^2 (0.5 gpm/ft^2) or less (Phase I Test #11, Phase II Test #3 and Test #10), the fire grew unabated to it's maximum size before the test was terminated due to the thermal conditions produced by the fire. The fire also grew in size during the test conducted with the 40.8 Lpm/m^2 (Phase II Test 11) application rate but the results have various interpretations.

The spray patterns of the ESFR sprinkler heads used during the test with an application rate of 40.8 Lpm/m^2 (Phase II Test 11) are much narrower than the standard pendent sprinkler heads used during the other tests. The higher flow rates and narrower spray patterns created turbulent air flows around the fire which serve to push the fire away from the spray pattern of the nozzles. During the test conducted with the ESFR sprinklers, the fire spread from the base of the fire apparatus to the southwest corner of the test area. The fire never crossed the spray pattern of a nozzle and remained burning in areas of lower water application rate (as determined by visual observations). While the fire spread and increased in size, it never approached the size of the fire observed during the previous water only tests. This was based on visual observations as well as the thermal measurements recorded during the test. It is uncertain how the fire would have behaved if the test was conducted in the center of a larger test area.

When extrapolating these results to typical aircraft hangars with closed head sprinklers, two bounding scenarios become apparent. If the conditions were such that an adequate number of sprinkler heads opened around the fire, bounding it on all sides, there is a high probability that the fire would have been contained (controlled) and would have only posed a threat to areas in close proximity to the origin of the fire. A more probable scenario, however, is the fire spreading away from the activated sprinklers resulting in a race between the size and location of the fire and the activation of the overhead sprinklers. The most likely outcome of this scenario is that fire continues to grow and the sprinklers continue to activate until the capacity of the pump supplying the sprinklers with water is exceeded and the fire burns out of control. Further research is required to validate these assumptions.

Additional information on the capabilities of water sprinklers to control and extinguish thin fuel spill fires is contained in reference [13].

6.5 Temperature Analysis

6.5.1 Overhead Temperatures

During these tests, the fire suppression systems were activated shortly after the spill fire reached an area of 9.3 m^2 (100 ft^2). The ceiling temperatures measured in the area directly above the fire were observed to rapidly increase to over 150°C (302°F) prior to the suppression system activation. Sprinkler response times observed for 79°C (175°F), quick response heads during previous hangar tests [2] suggest that a closed head system (quick response) in a hangar application would have activated in roughly the same time frame. These previous tests also show that conventional sprinkler response time models should not be used for hangar applications and will not be included in this analysis.

During Phase I of this investigation, an instrumented steel beam was installed directly above the test area. The beam was installed flush to the ceiling approximately 0.3 m (1 ft) above the sprinkler heads. The beam was also installed during Phase II but due to technical difficulties, the data was not recorded.

Throughout Phase I of this investigation, the steel beam temperatures followed the same trends as the gas temperatures measured just outside of the test area. The beam temperatures exhibited the same rate-of-rise characteristics of the gas temperatures but typically lagged 50°C (90°F) behind. The beam temperatures and gas temperatures are shown in Figure 18 for Test I-3. Due to the similarity in measurements between the beam and gas temperatures, it can be assumed that the gas temperatures measured during Phase II are representative of the exposures/temperatures of the structural members in the space.

After the system was activated and the spill fire was extinguished, the ceiling/hot gas temperatures were observed to approach a steady-state value. The magnitude of this steady-state value was observed to be a function of the heat release rate of the fire apparatus. The average

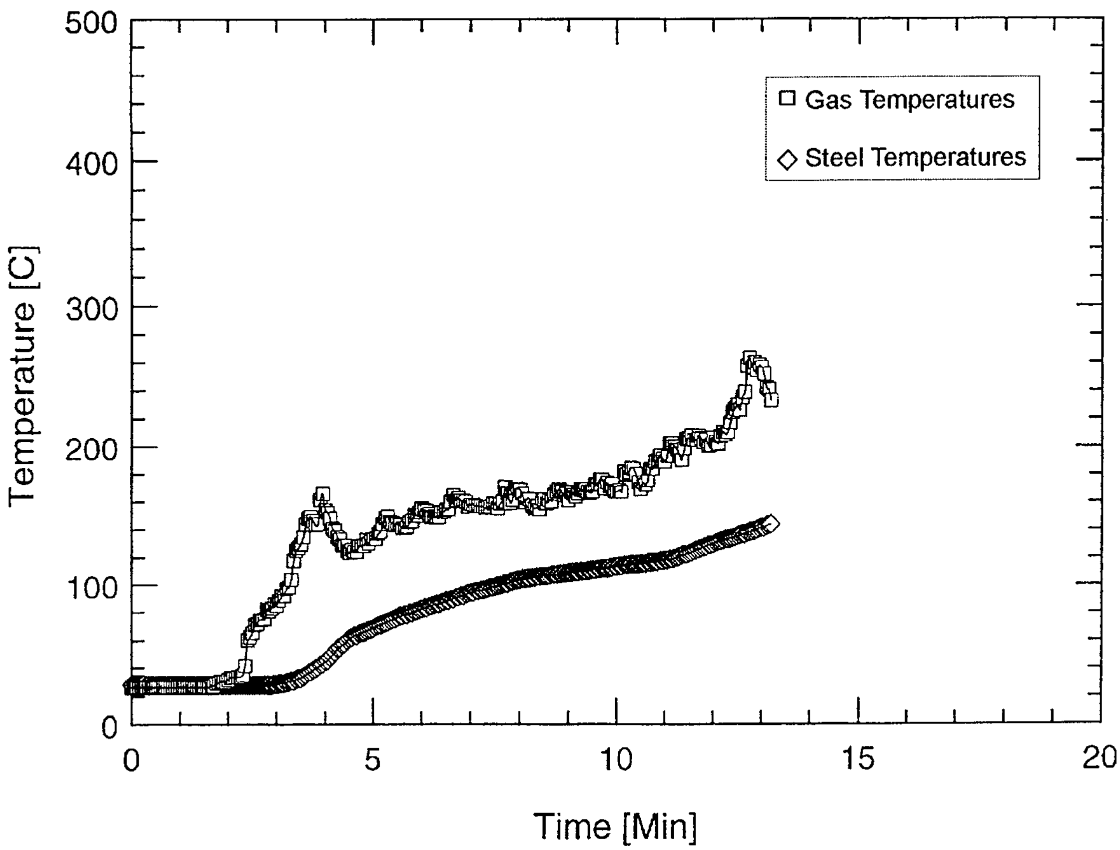


Figure 18 – Steel beam and hot gas temperature comparison

steady-state ceiling/hot gas temperatures for the three fire scenarios were 200°C (392°F) for Fire Scenario 1, 90°C (198°F) for Fire Scenario 2 and 40°C (104°F) for Fire Scenario 3 . These temperatures were proportional to the heat release rate of the fire apparatus (excluding the spill fire). A temperature history for each of the three fire scenarios is shown in Figure 19.

The cooling provided by the various sprinkler application rates included in this evaluation is shown in Figure 20. As shown in this Figure, sprinkler application rates up to 10.2 Lpm/m^2 (0.25 gpm/ft^2) had only a minimal effect on cooling the upper gas layer and structural steel members in the simulated aircraft hangar fire scenarios. Drop size distribution is one of the primary factors associated with the lack of cooling of the hot layer provided by the sprinkler system. These tests were designed and conducted at the minimum nozzle pressure allowed by NFPA 13. Higher nozzle pressures would produce smaller droplets and would potentially increase the cooling efficiency of the system. If the intent of the overhead sprinkler system is to protect the structural integrity of the hangar, modifications to the system should be considered. Direct water impingement from the sprinklers on the structural members is one option. Pendent sprinkler heads installed in an upright position may accomplish the desired cooling/wetting.

Independent of the operating pressure of the system, the operation of overhead sprinklers should provide significant cooling of adjacent aircraft due to wetting of the aircraft surfaces. This is obviously a function of the orientation of the surface for both the wetting of the surface and the radiant exposure to the surface. The protection/cooling of exposures provided by overhead sprinklers is directly related to the application rate of the system. For example, an application rate of 6.5 Lpm/m^2 (0.16 gpm/ft^2) can absorb 35 kW/m^2 if the water removes heat from the object and in the process the water temperature is raised to 100°C (boiling). If all of the water is evaporated, over 250 kW/m^2 would be absorbed. The magnitude of the energy absorbed by the water may effectively negate the radiant exposures to adjacent aircraft.

6.5.2 Concrete Temperatures

The temperature of the concrete in the test area was measured in the center of the fuel spill at two depths; flush with the surface and at a depth of 1.25 cm (0.5 in) below the surface. The maximum surface temperatures occurred directly after the fuel spill reached steady-state burning and typically ranged from 200-250°C (400-480°F). The temperatures measured at a depth of 1.25 cm (0.5 in) lagged slightly behind the surface temperature with the maximum temperature occurring about 10-15 seconds later and typically ranged from 30-80°C (86-175°F). The maximum concrete temperatures recorded at a depth of 1.25 cm (0.5 in) below the surface are shown in Tables 1 and 2 for each test.

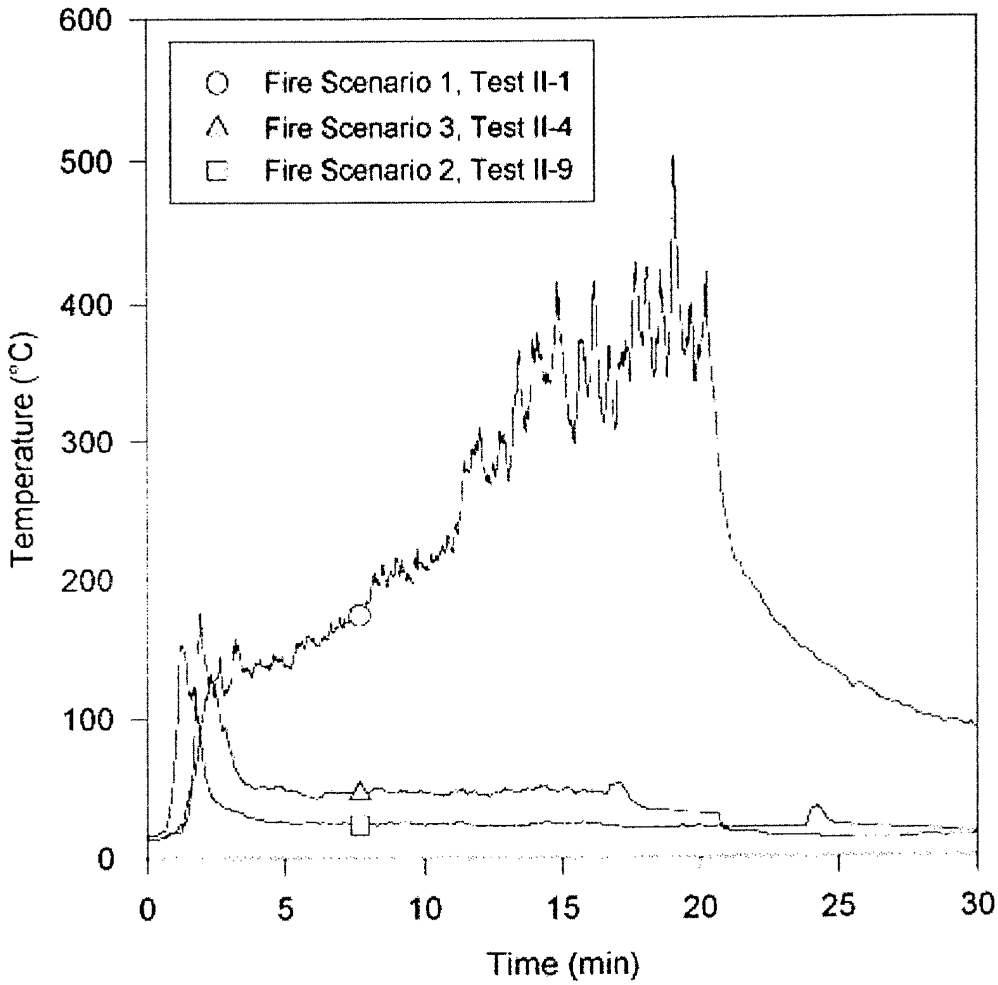


Figure 19 – Ceiling temperature histories

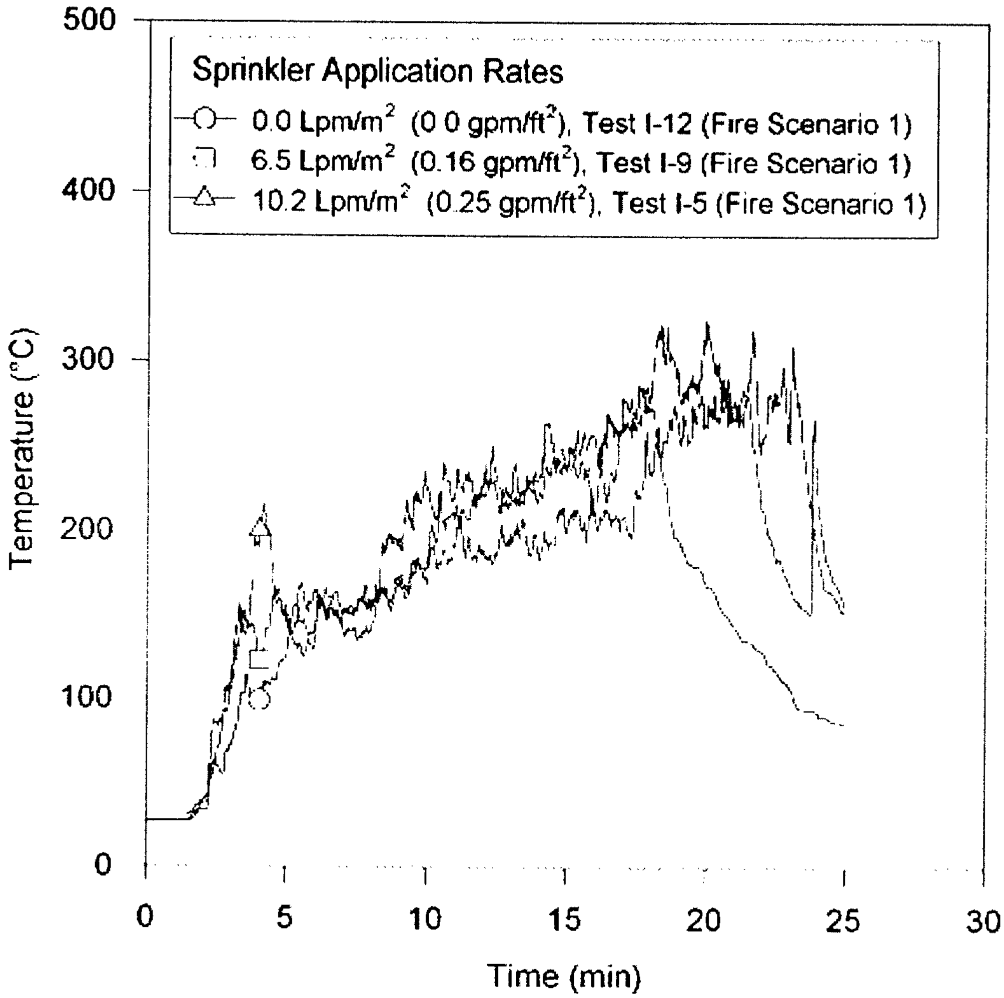


Figure 20 – Cooling effects of sprinklers

6.6 Exposures to Adjacent Aircraft

6.6.1 Point Source Model Description

Radiation measures were made at five locations around the test area; two at 2-3 m (10 ft) from the center of the spill and one at each of the following locations 6 m (20 ft), 9 m (30 ft) and 12 m (40 ft). When the fire was burning at its maximum size (maximum spill fire area), the average radiant flux measured at these locations is as shown in Table 3. These measurements were relatively consistent between tests and appear to be proportional to the inverse square of the distance from the target to the source, a characteristic of a point source model [14].

Table 3. Typical Radiant Heat Flux Measurements

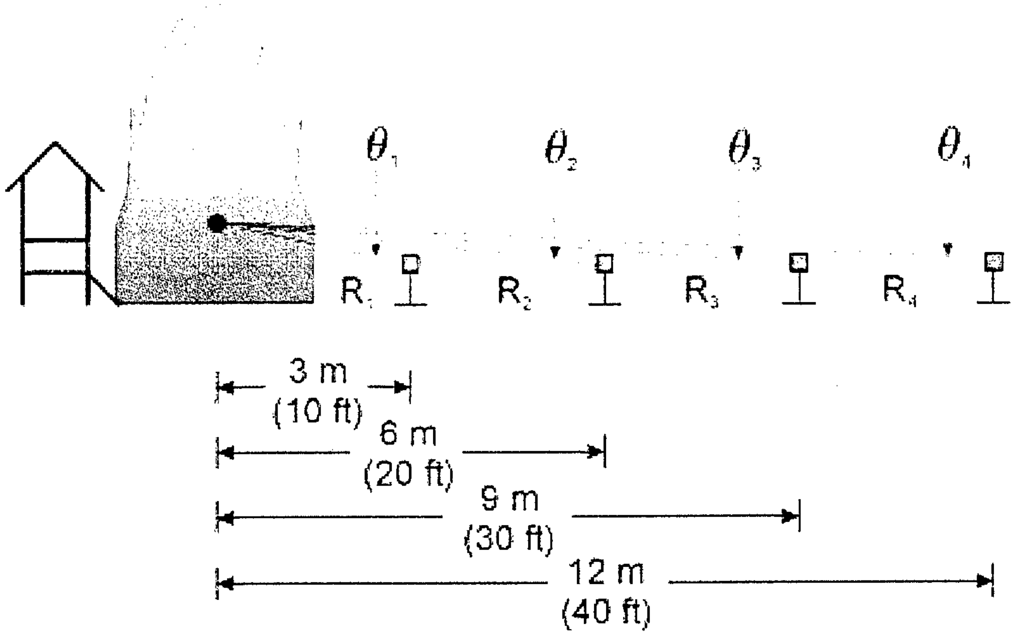
Distance From Fire m (ft)	Radiative Heat Flux kW/m^2
3.0 (10)	35
6.0 (20)	12
9.0 (30)	5
12.0 (40)	3

A point source model is the simplest configuration model used to predict radiation to a target. More realistic fire shapes give rise to more complex equations. The incident radiative heat flux, $\dot{q}''$, predicted by a point source model is given by the following equation, as shown in Figure 21.

$$\dot{q}'' = \frac{\dot{Q}_R \cos\theta}{4 \pi R^2} \tag{1}$$

The variable $\dot{Q}_R$ is the total radiative energy output of the fire, θ is the angle between the vector normal to the target and the line of sight from the target to the point source location, and R is the distance from the point source to the target.

When applying a point source model to a given configuration, caution should be exercised when estimating the distance between the target and the point source. For example, during these tests when the pool/spill fire is growing, the distance between the target and the fire can be approximated assuming the point source is the center of the pool just above ground level. Once the fire has reached it's maximum size and the burning rate approaches a maximum steady-state value ($\dot{m}''_\infty$), the point source is still located in the center of the spill but at an elevation



Fire Size Prediction $\dot{Q} = \dot{M}\Delta H$ (1)

Radiation Energy Output $\dot{Q}_R = X_R\dot{Q}$ (2)

Radiation to a Target $\dot{q}_R'' = \dfrac{\dot{Q}_R}{4\pi R^2}\cos\theta$ (3)

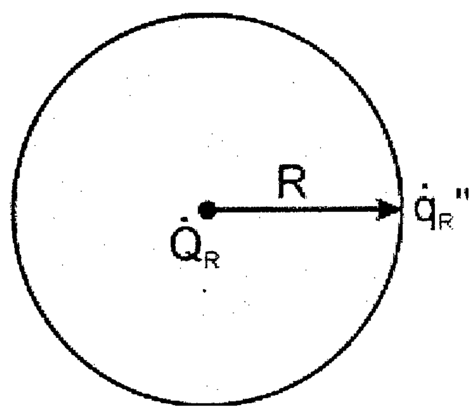


Figure 21 – Exposures to adjacent aircraft (point source model)

approximately half the continuous height of the flame. The flame height can be estimated using correlations developed by either Heskestad [15] or McCaffrey [16] and the distance between the point source and the target can be calculated using trigonometric functions. Consequently, due to the nature of these calculations, the point source model is more robust for estimating radiation to targets located some distance away from the fire but becomes more sensitive to the distance calculation as the distance between the target and the fire is reduced.

There was also a concern that there may be a difference between what has been defined as a spill fire as compared to a pool fire with respect to predicting exposures. During these tests, the spill fire was observed to flow across the deck until the spill fire area was adequate to burn all of the fuel being spilled. Once the spill fire reached its maximum size (which is a function of fuel spill rate and drainage), the spill fire began to behave as a pool fire with burning rates approaching the maximum theoretical valve ($\dot{m}''_\infty$). This is supported by the fire size and flame height measurements made during these tests. In conclusion, there is a difference between the exposures resulting from a spill fire and a pool fire. However, the spill fire is transient in nature and in a majority of cases should approach the conditions produced by a pool fire. The conservative approach to predicting the exposures to adjacent aircraft would incorporate the burning characteristics of a pool fire [17].

6.6.2 Point Source Model Application and Comparison

Estimating the thermal radiation incident upon an object involves the following three step process:

(1) Determination of geometric characteristics of the pool fire; i.e., the determination of burning rate and physical dimensions of the fire;

(2) Determination of thermal radiation characteristics of the fire; i.e., the determination of average emissive power of the flames; and

(3) Calculation of the incident radiant flux at the target location.

For a known fuel flow/spill rate, the maximum fire size can be estimated using the following equation:

$$\dot{Q} = \dot{m}\,\Delta H_c \qquad (2)$$

$\dot{Q}$	=	the maximum heat release rate (kW),
$\dot{m}$	=	Mass burning rate (in our case fuel flow rate), (kg/s)
ΔH_c	=	heat of combustion of the fuel (kJ/kg).

For a fuel flow rate of 10 gpm of JP-8 or JP-5, the maximum heat release rate equals approximately 22 MW.

The radiative energy output ($\dot{Q}_R$) is given by the radiative fraction, χ_R, multiplied by the total heat release rate (Q):

$$\dot{Q}_R = \chi_R \dot{Q} \tag{3}$$

where the radiative fraction, χ_R, is a function of pool area/diameter [18]. These values typically range from 0.2 to 0.05 and decrease with increased burning area. For pool diameters in the range evaluated during these tests (3-4 meters), the radiative fraction is roughly 0.2. This corresponds to a radiative energy output of 4.4 MW.

Assuming that the radiation is normal to the surface (θ=0) and that R can be approximated as the distance from the target to the center of the spill, equation (1) can be applied to predict the radiation at the target location.

A comparison between the predicted and measured radiant heat fluxes is shown in Figure 22. The line on this Figure represents the predicted value at various distances from the source. The symbols represent the radiant heat fluxes measured during these tests. The data collected during this test series shows, for the most part, good agreement with that predicted by the model. As the distance between the source and the target is reduced, assumptions pertaining to the R dimension have a greater impact on the accuracy of the predicted exposure, and consequently result in deviations between the predicted and measured heat fluxes at these close locations.

The same basic comparison between the predicted and measured radiant heat fluxes was also conducted on set of data collected during previous hangar tests [2]. This comparison is shown in Table 4.

As shown in Table 4, the radiant heat fluxes predicted using the measured heat release rates of these fires are approximately 75% of that measured during the test. There are two possible sources for this variation. The first source relates to the measured heat release rates of these fires. The heat release rates of these fires were determined using the mass loss rate of the pan multiplied by the heat of combustion of the fuel. These measured values are approximately 75% of the predicted theoretical heat release rates of pan fires of this size. If a theoretical heat release rate is used in the exposure prediction, the predicted results are typically within 10% of the measured value. The second possible cause for this variation is the radiative fraction used in the calculation. If a radiative fraction of 0.25 is selected rather than 0.20, the predicted results again fall within 10% of the measured value.

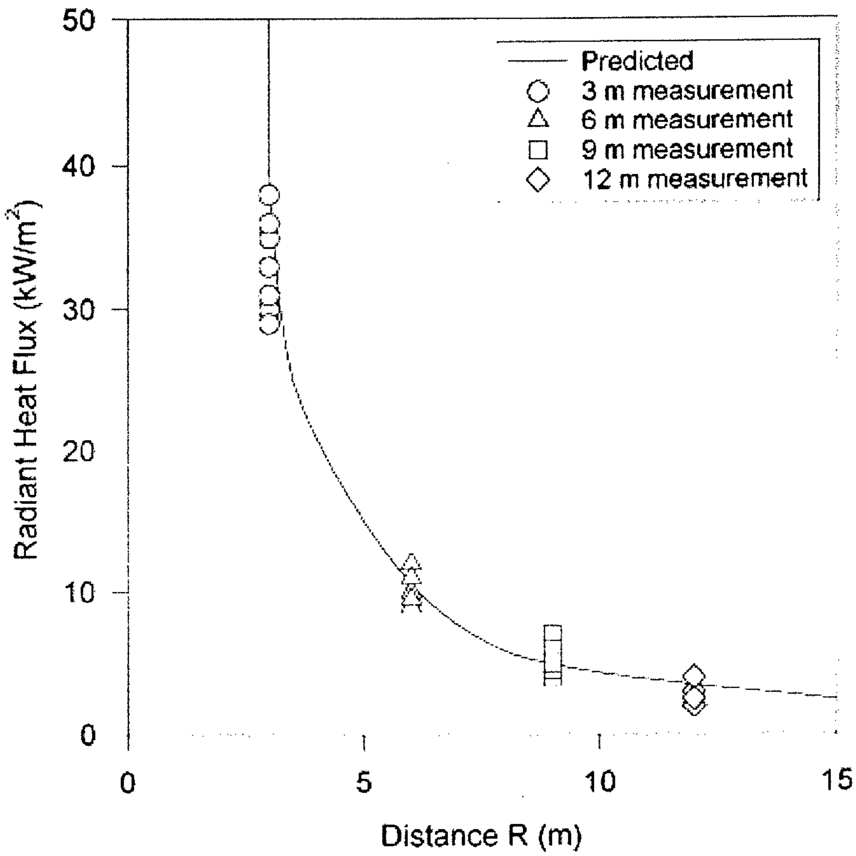


Figure 22 – Comparison between predicted and measured radiant heat fluxes

Table 4. Radiant Heat Flux Exposure Comparison

Test	Pan Size m^2 (ft^2)	Theoretical HRR MW	Measured HRR MW	Distance m (ft)	Measured Flux kW/m^2	Calculated Flux Using Measured HRR	Calculated Flux Using Theoretical HRR
Warm Climate Tests							
4	1.8 (19.3)	3.7	3.0	5.0 (16.4)	2.6	1.9	2.4
5	3.1 (33.3)	7.0	6.8	5.0 (16.4)	5.4	4.3	4.5
7	3.1 (33.3)	7.0	5.6	5.0 (16.4)	4.7	3.6	4.5
6b	4.9 (52.7)	11.1	7.7	5.0 (16.4)	6.8	5.0	7.2
Cold Climate Tests							
14	4.9 (52.7)	11.1	7.9	7.1 (23.3)	3.5	2.5	3.5
15	9.0 (96.7)	19.7	15.7	7.6 (24.9)	5.0	4.3	5.4
17	9.0 (96.7)	19.7	14.3	7.2 (23.6)	5.5	4.3	5.4
18	3.1 (33.3)	7.0	4.9	4.2 (13.8)	7.0	4.4	6.3
20	9.0 (96.7)	19.7	14.6	7.2 (23.6)	5.5	4.4	5.4
21	21.2 (228.0)	47.3	33.0*	7.2 (23.6)	9.0	10.0	14.5

* Estimated heat release rate based on previous data.

In summary, a technique for predicting exposures to aircraft resulting from large fuel spill fire scenarios has been developed. The technique compares favorably to the experimental data collected during this and previous investigations [2]. The damage potential from these exposures is a function of the spill fire scenario, as well as the material characteristics of the aircraft. The point source model will be used in a collateral damage assessment for establishing optical detector performance [19].

7.0 SUMMARY

Twenty three full-scale fire tests were conducted to evaluate the effects of overhead water sprinklers on AFFF foam blankets. One AFFF application rate (4.0 Lpm/m^2 (0.1 gpm/ft^2)) and two sprinkler application rates were included in this evaluation (6.5 and 10.2 Lpm/m^2 (0.16 and 0.25 gpm/ft^2)). The tests were conducted against a range of spill fire scenarios. The spill fires were produced using either JP-5 or JP-8 aviation fuels and were evaluated on a concrete pad with similar drainage characteristics of typical Navy hangars.

The results show that the use of water sprinklers (with application rates up to 10.2 Lpm/m^2 (0.25 gpm/ft^2)) in conjunction with a low level AFFF fire suppression system (with an application rate of 4.0 Lpm/m^2 (0.1 gpm/ft^2)) had minimal effects on the ability of the system to suppress the fire and resist burnback. In all tests, the low level AFFF system was capable of quickly extinguishing the test fire (control ~ 30 sec and extinguishment ~ 1:00) independent of the sprinkler application rate. The time required for the fire to burnback across the fuel surface was apparently a function of the drainage characteristics of the hangar and was only slightly affected by the application of water through the overhead sprinklers. The tests also show that the flashpoint of the fuel has an effect on the control, extinguishment and burnback resistance capabilities of the system. Although the burnback times for the lower flashpoint fuels were faster than the higher flashpoint fuels, the duration of protection was not significantly altered. In summary, these tests show that overhead water sprinklers (with application rates up to 10.2 Lpm/m^2 (0.25 gpm/ft^2)) have minimal effect on AFFF foam blankets, independent of the test fuel, fire scenario and sprinkler application rate. The tests show that a combined low level AFFF extinguishing system operating in conjunction with an overhead water sprinkler system will provide adequate protection for the hangar during AFFF discharge but the protection in terms of burnback resistance, may be lost shortly (a few minutes) after the end of AFFF discharge.

The fire suppression capabilities of an overhead water only sprinkler system were also evaluated. Three sprinkler application rates were included in this evaluation (10.2, 20.4 and 40.8 Lpm/m^2 (0.25, 0.5 and 1.0 gpm/ft^2)). The results show that sprinkler application rates of 20.4 Lpm/m^2 (0.5 gpm/ft^2) or less have little or no capabilities to control and/or extinguish the Class B fires evaluated in these tests. Higher application rates were observed to have varying capabilities and require further evaluation.

The results of these tests show that overhead sprinklers provide only minimal cooling of the hot gas layer for the application rates included in this evaluation. Consequently, the overhead sprinklers provide limited protection for the hangar structure. The overhead sprinklers can however, provide significant cooling of adjacent aircraft.

Radiation measurements made during these tests support the use of a point source model in estimating the exposures to adjacent aircraft from spill fire scenarios. This type of model does however tend to lose accuracy at locations in close proximity to the fire.

8.0 CONCLUSIONS

The data show that a low level AFFF system alone can achieve rapid fire control and extinguishment without the use of overhead sprinklers. This is consistent with data in the literature [20]. In these tests, with the nozzles adjusted/positioned in a less-than-optimum configuration, control times ranged from 20-40 sec and total extinguishment of the spill fire was generally achieved in 60 seconds. This is consistent with the requirements of NFPA 409 design objectives of 30 sec for control and 60 sec for extinguishment after system activation [7]. It has been demonstrated that the operation of overhead water sprinklers does not degrade the performance of the low level system during AFFF discharge. Design criteria for Navy hangar protection can be revised to incorporate AFFF application from only the low level system, combined with overhead closed head quick response water sprinklers with the recognition that burnback may occur shortly after the foam supply is expended.

The revised fire suppression system design will rely on several key parameters. These include rapid and accurate detection of a fire, improved low level discharge characteristics/nozzle design, adequate AFFF discharge duration and reliable operation of the low level AFFF system. Work is being performed to establish appropriate performance specifications for optical detectors installed in hangars [19]. This work is an extension of extensive work conducted by the National Research Council of Canada (NRC) [21]. Alternative low level nozzle designs are also being evaluated. These designs will consist of floor/drain level installations using a 4.0 Lpm/m^2 (0.10 gpm/ft^2) application rate [4]. An AFFF design duration of 10 minutes has been established by NAVFAC as a reasonable time for the fire department to respond and supplement the effects of the fixed fire suppression system. Efforts are also underway to identify and improve on AFFF system components which reduce the reliability and increase the maintenance requirements of the system.

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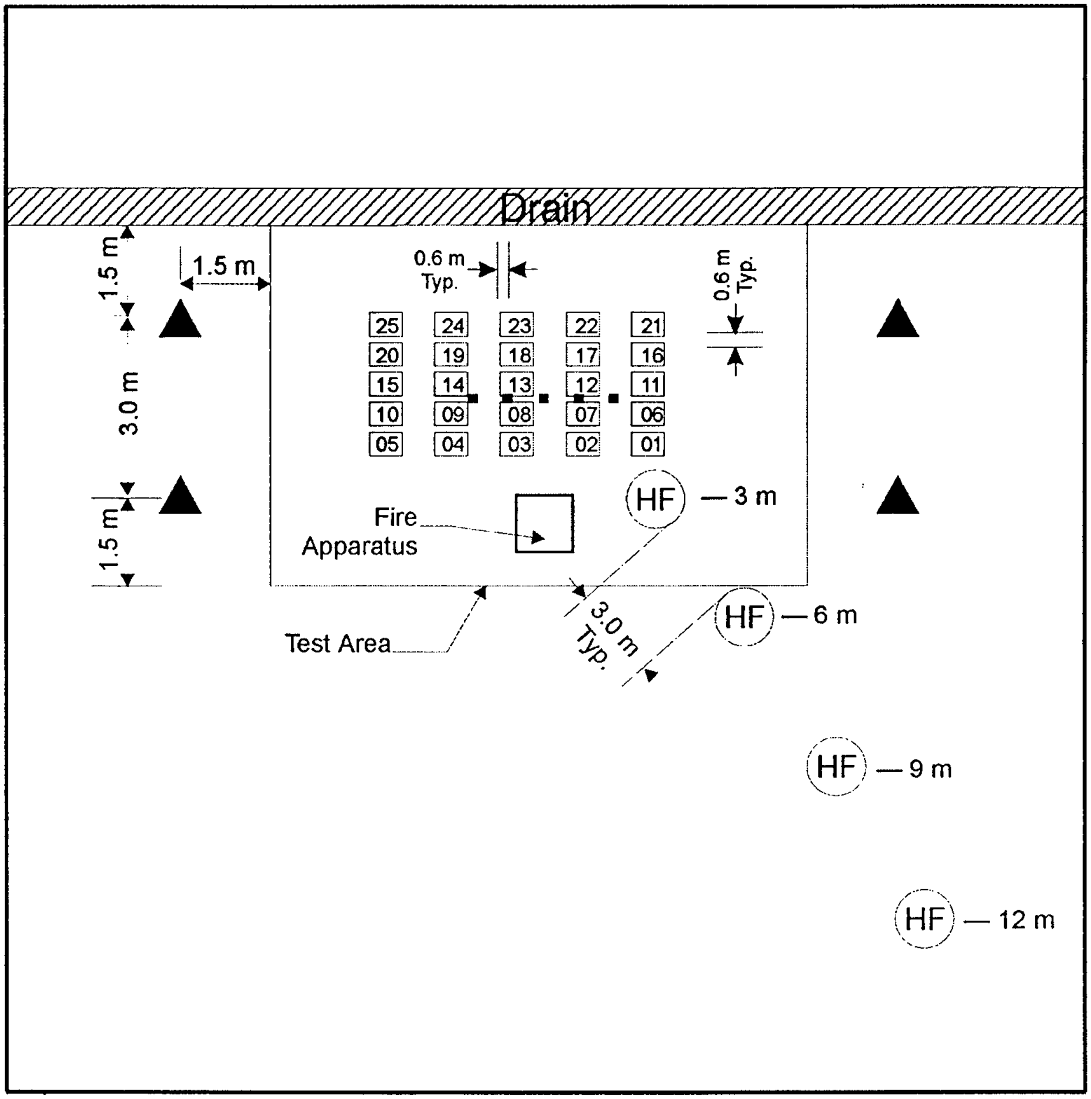
Appendix A

Test Data

CONTENTS



XX Fire/Grid Thermocouples (0.25 m above deck)

▪ Steel Thermocouples (Beam flush with ceiling)

▲ Ceiling Thermocouples (13.7 m above the deck; 5.0 cm below ceiling)

HF Heat Flux Measurements (0.3 m above the deck)

Figure A1 - Instrumentation layout

Table A-1. Aircraft Hangar Suppression System Evaluation – Phase I Summary Data

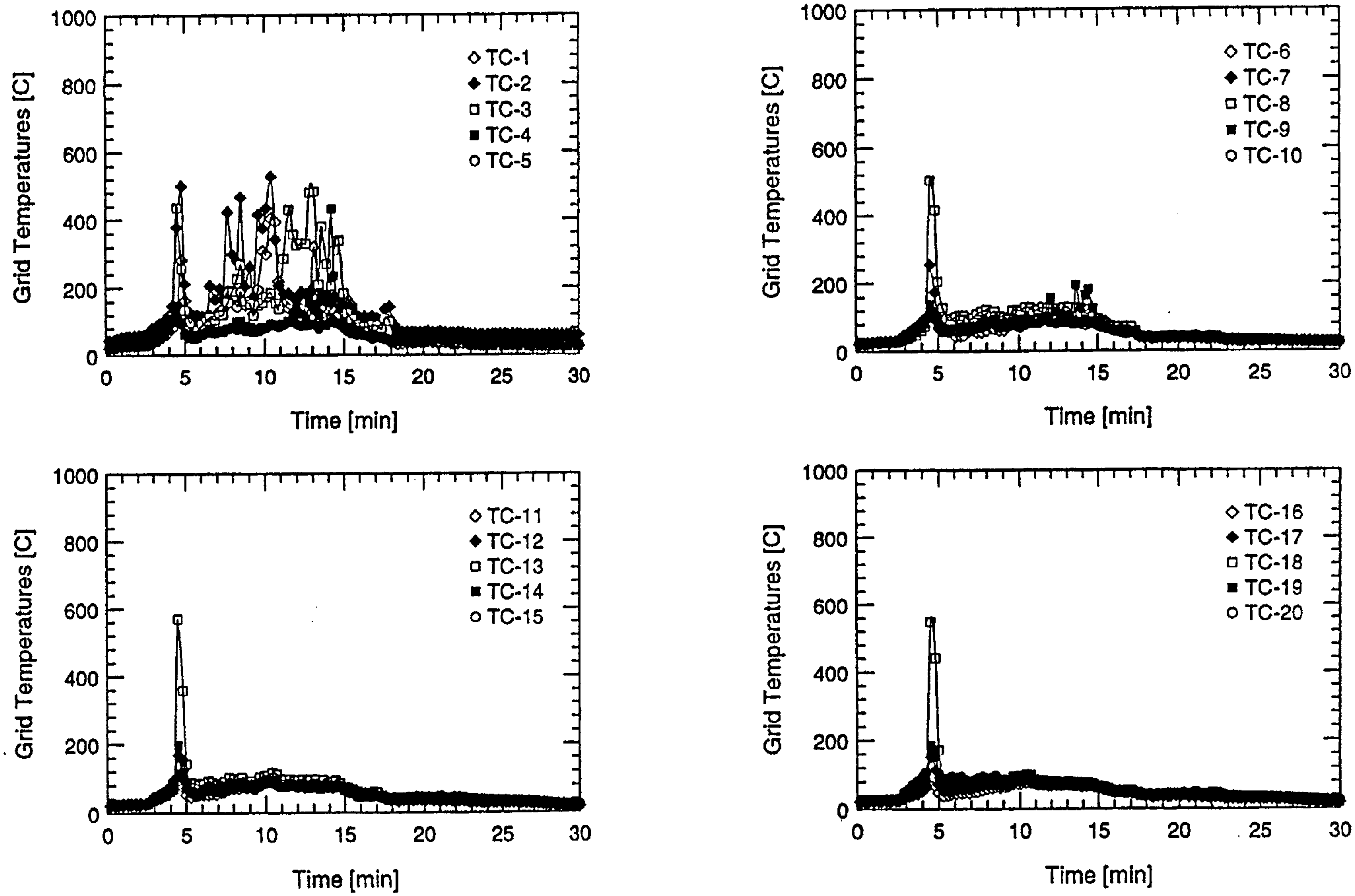
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Fuel	JP8	JP5	JP5	JP8	JP8	JP5	JP8	JP8	JP8	JP8	JP5	JP8
Fire Scenario	1	1	1	1	1	1	1	1	1	1	1	1
Fuel Flow Rate, Lpm (gpm)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)
Fire Scenario - Cascade	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full
AFFF Duration (min)	5:00	5:00	10:00	10:00	10:00	10:00	5:00	5:00	10:00	5:00	N/A	10:00
Sprinkler Application Rate, Lpm/m² (gpm/ft²)	0.0 (0.0)	0.0 (0.0)	6.5 (0.16)	6.5 (0.16)	10.2 (0.25)	10.2 (0.25)	6.5 (0.16)	6.5 (0.16)	6.5 (0.16)	6.5 (0.16)	10.2 (0.25)	0.0 (0.0)
Sprinkler Actuation Time	N/A	N/A	SIM	SIM	SIM	SIM	SIM	SIM	SIM	DELAYED	ONLY	N/A
Fuel Spill Area, m² (ft²)	7.6 (82)	6.7 (72)	7.4 (80)	8.0 (86)	8.9 (96)	8.2 (88)	7.6 (82)	7.8 (84)	7.6 (82)	8.0 (86)	7.6 (82)	7.8 (84)
Fuel Temperature, °C (°F)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)
Concrete Temperature, °C (°F) depth = 1.25 cm (0.5 in)	27 (80)	32 (90)	29 (85)	27 (80)	32 (90)	32 (90)	35 (95)	29 (85)	32 (90)	32 (90)	29 (85)	32 (90)
Flame Height at Actuation, m (ft)	12.2 (40)	12.2 (40)	12.2 (40)	10.7 (35)	9.2 (30)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)	10.7 (35)
Est. Heat Release Rate, MW	21	19	22	22	23	22	21	21	21	22	21	21
Ceiling Temperature, °C (°F)	200 (392)	200 (392)	220 (428)	220 (428)	200 (392)	190 (374)	210 (410)	210 (410)	190 (374)	210 (410)	210 (410)	210 (410)
Heat Flux at Actuation, kW/m²												
3.0 m (10 ft)	45.0	38.0	30.0	50.0	32.0	31.0	33.0	31.0	25.0	31.0	47.0	28.0
6.1 m (20 ft)	15.5	13.0	10.0	22.0	10.0	12.0	11.0	12.0	9.0	10.0	12.0	9.0
9.1 m (30 ft)	7.0	5.5	4.0	12.0	5.0	5.5	6.0	7.0	6.0	5.0	6.5	5.0
12.2 m (40 ft)	5.0	4.0	2.5	8.0	3.5	4.0	4.0	5.0	4.0	3.0	4.5	3.5
90% Extinguishment Time (s)	40	35	16	29	25	22	17	14	17	17	No	23
100% Extinguishment Time (s)	45	50	25	45	45	27	23	30	32	47	No	34
Burnback Time (min) (After AFFF Discharge)	6:00	5:00	7:00	5:00	7:00	5:00	3:00	3:00	6:00	4:00	N/A	6:00

SIM - The sprinkler system and low level AFFF system were activated simultaneously.
DELAYED - The sprinkler activation was delayed until after the fire was extinguished.
N/A - The sprinklers were not activated during the test.
ONLY - The test was conducted with only the overhead sprinklers.

Table A-2. Aircraft Hangar Suppression System Evaluation – Phase II Summary Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11
Fuel	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8	JP8
Fire Scenario	1	1	3	3	3	3	2	2	2	2	2
Fuel Flow Rate, Lpm (gpm)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	38 (10)	57 (15)	57 (15)	57 (15)	57 (15)	57 (15)
Fire Scenario - Cascade	Full	Full	No	No	No	No	½	½	½	½	½
AFFF Duration (min)	10:00	10:00	N/A	10:00	10:00	10:00	10:00	10:00	10:00	N/A	N/A
Sprinkler Application Rate, Lpm/m^2 (gpm/ft^2)	0.0 (0.0)	6.5 (0.16)	10.2 (0.25)	0.0 (0.0)	10.2 (0.25)	6.5 (0.16)	6.5 (0.16)	10.2 (0.25)	0.0 (0.0)	20.4 (0.5)	40.8 (1.0)
Sprinkler Actuation Time	N/A	SIM	SIM	N/A	SIM	SIM	SIM	SIM	N/A	ONLY	ONLY
Fuel Spill Area, m^2 (ft^2)	8.8 (95)	8.4 (90)	7.9 (85)	7.9 (85)	7.9 (85)	7.9 (85)	8.4 (90)	8.4 (90)	7.9 (85)	N/A	N/A
Fuel Temperature, °C (°F)	200 (400)	200 (400)	43 (110)	32 (90)	38 (100)	35 (95)	91 (195)	91 (195)	93 (200)	77 (170)	82 (180)
Concrete Temperature, °C (°F) depth = 1.25 cm (0.5 in)	22 (71)	19 (66)	20 (68)	16 (60)	9 (48)	11 (51)	9 (48)	25 (77)	25 (77)	29 (85)	28 (71)
Flame Height at Actuation, m (ft)	9.8 (32)	9.8 (32)	9.2 (30)	9.8 (32)	9.2 (30)	9.2 (30)	10.7 (35)	9.2 (30)	9.2 (30)	N/A	N/A
Est. Heat Release Rate, MW	23	22	21	22	21	21	24	22	21	N/A	N/A
Ceiling Temperature, °C (°F)	200 (392)	190 (374)	120 (248)	25 (77)	20 (68)	22 (72)	30 (86)	25 (77)	40 (104)	35 (95)	30 (86)
Heat Flux at Actuation, kW/m^2 3.0 m (10 ft) 6.1 m (20 ft) 9.1 m (30 ft) 12.2 m (40 ft)	 36.0 10.0 7.0 3.0	 30.0 12.0 6.0 4.0	 N/A	 30.0 9.0 4.0 2.0	 33.0 9.0 4.0 2.0	 31.0 9.0 4.0 2.0	 38.0 11.0 5.0 2.5	 29.0 9.5 4.5 2.5	 36.0 11.0 5.0 2.5	 N/A	 N/A
90% Extinguishment Time (s)	23	30	No	25	47	36	39	37	41	No	No
100% Extinguishment Time (s)	39	82	No	57	70	49	54	53	60	No	No
Burnback Time (min) (After AFFF Discharge)	4:00	5:00	N/A	13:00	4:00	4:00	4:00	3:00	5:00	N/A	N/A

SIM - The sprinkler system and low level AFFF system were activated simultaneously.
DELAYED - The sprinkler activation was delayed until after the fire was extinguished.
N/A - The sprinklers were not activated during the test.
ONLY - The test was conducted with only the overhead sprinklers.



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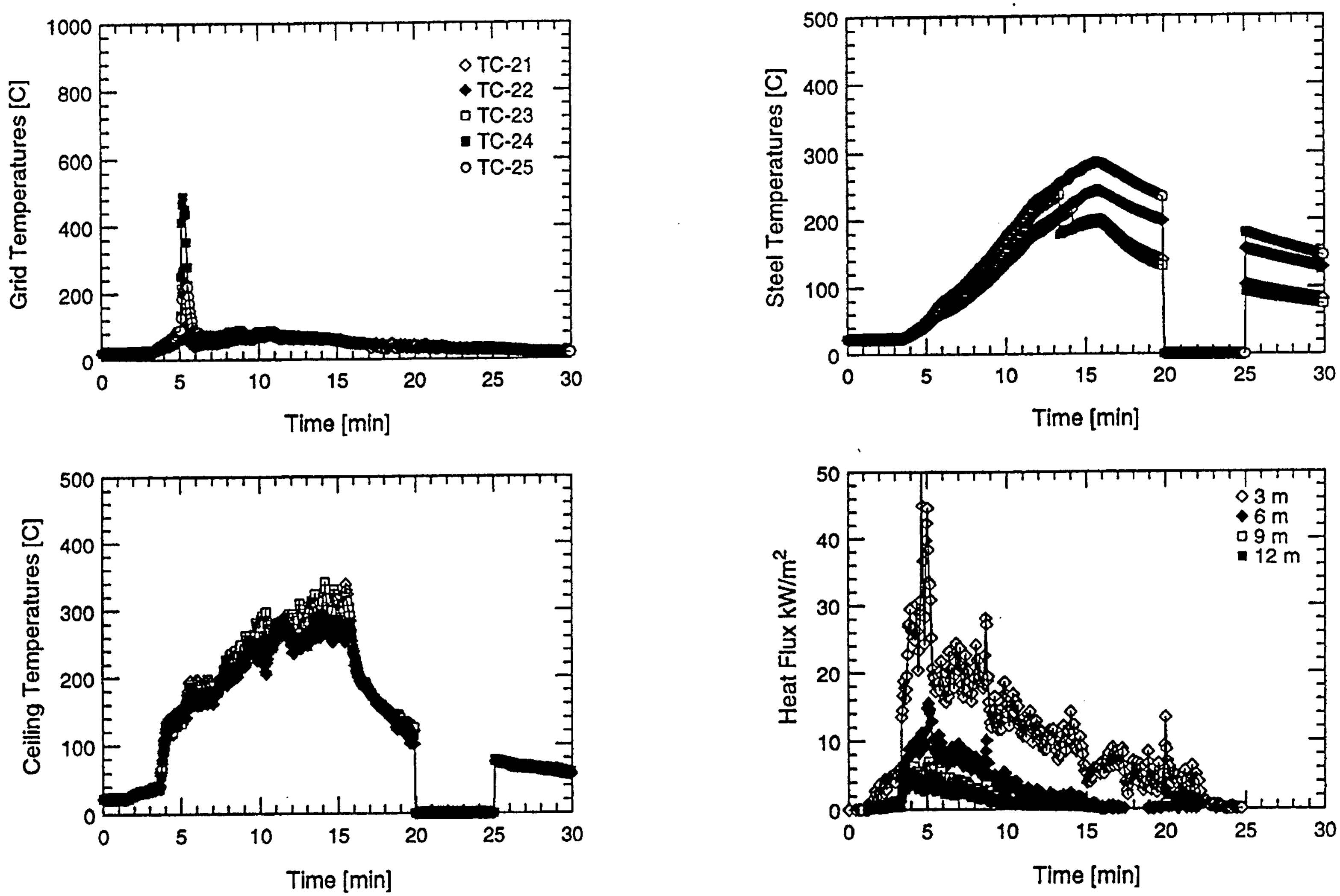

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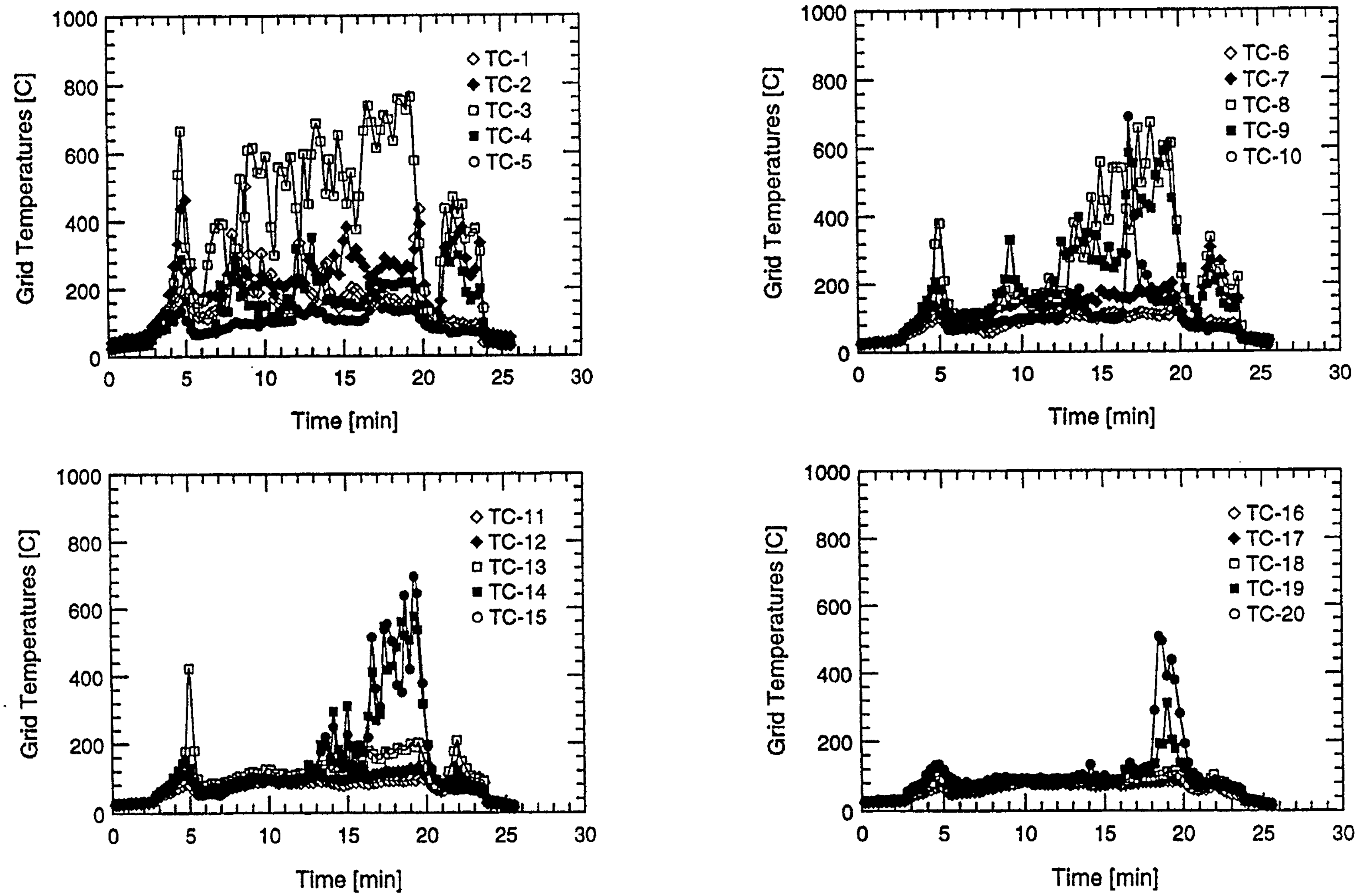

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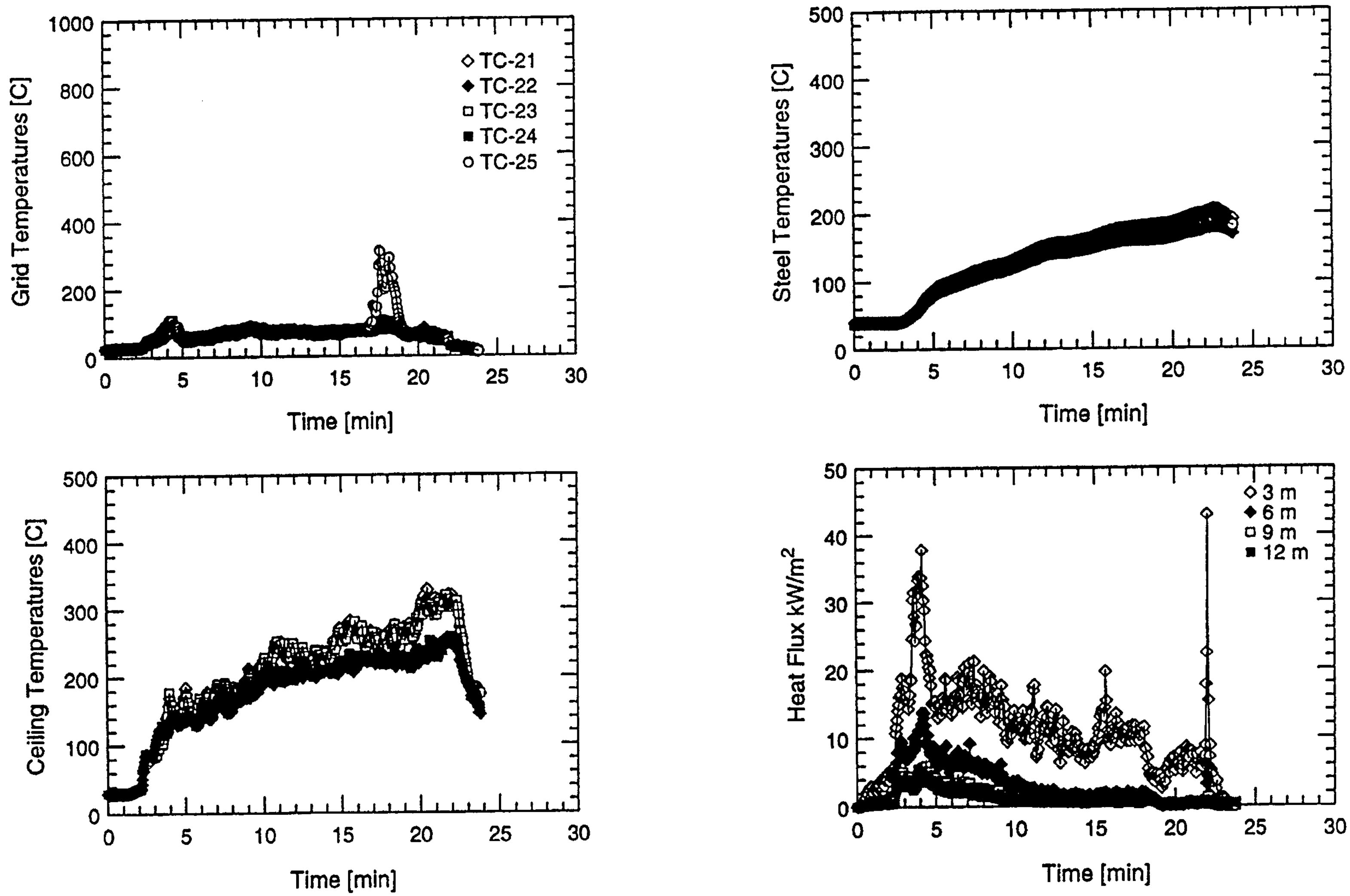

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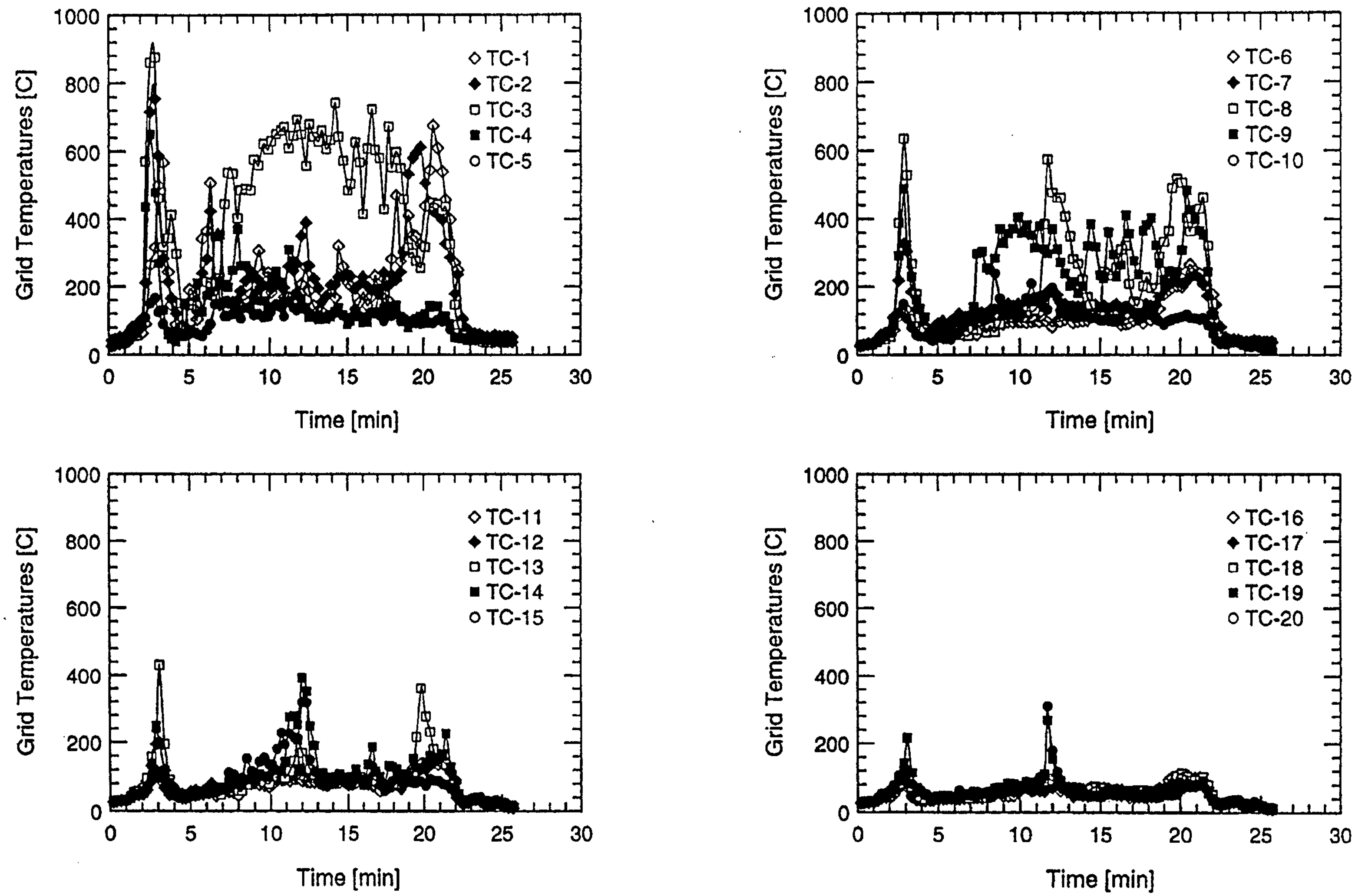

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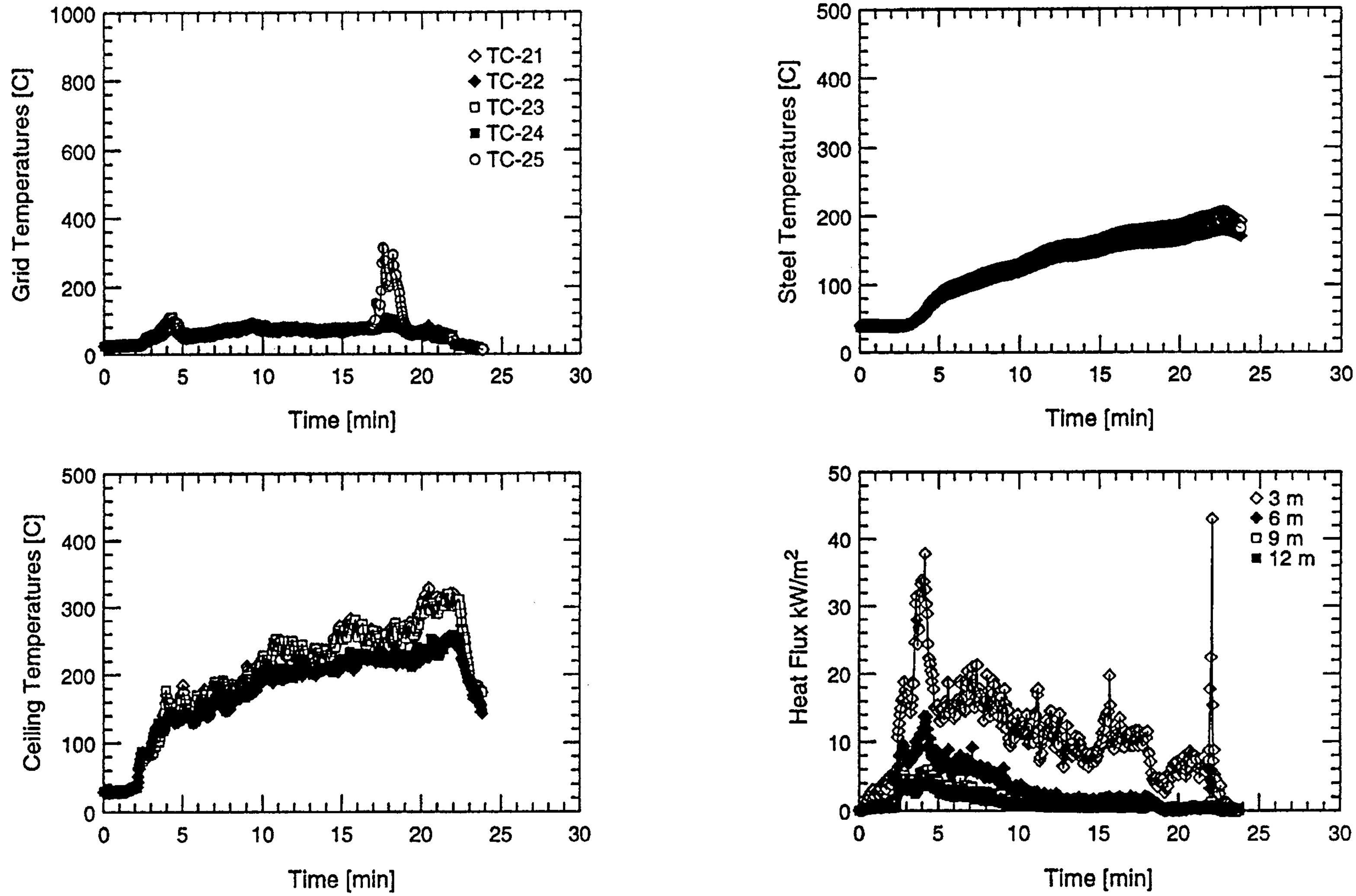

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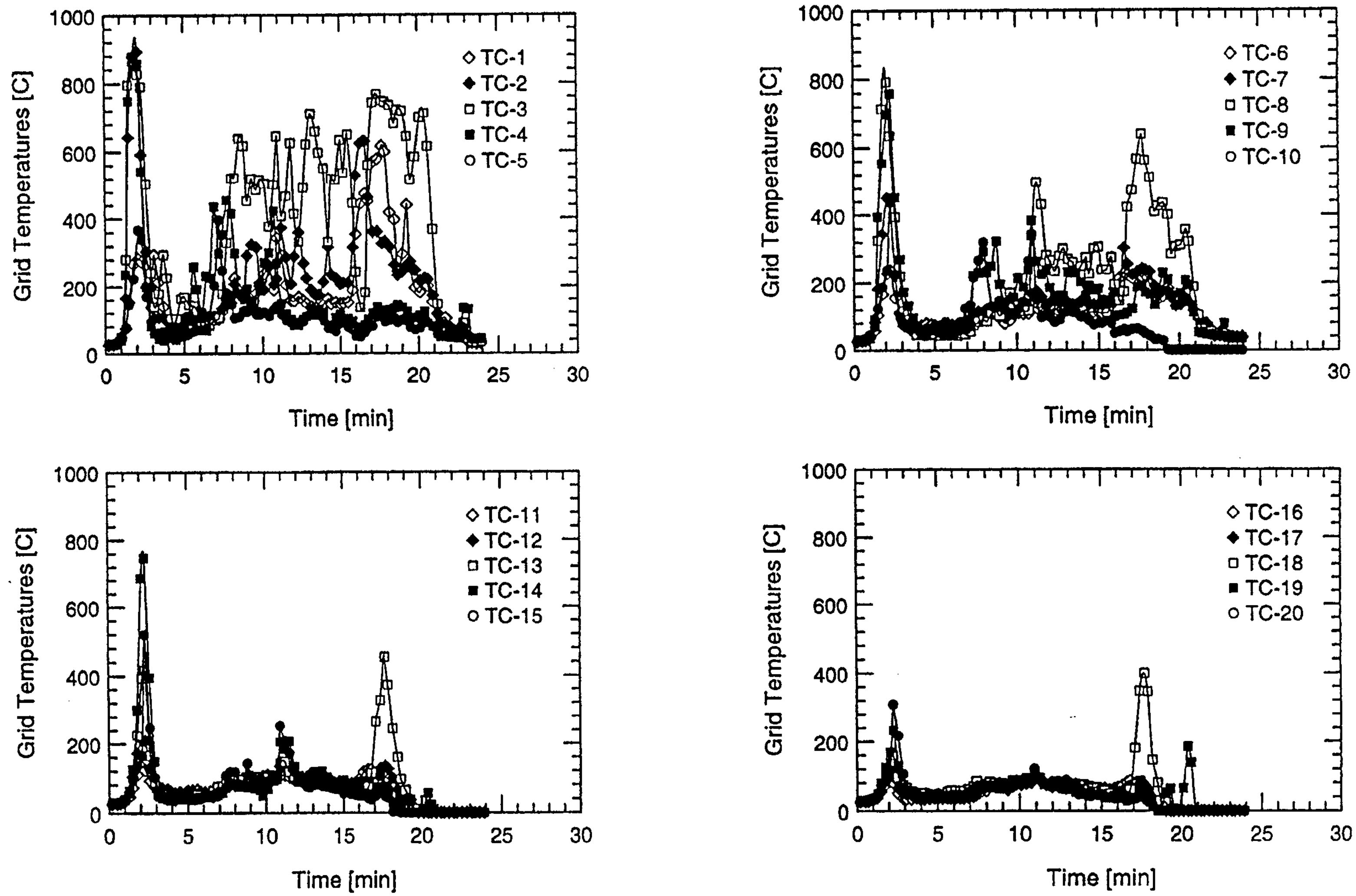

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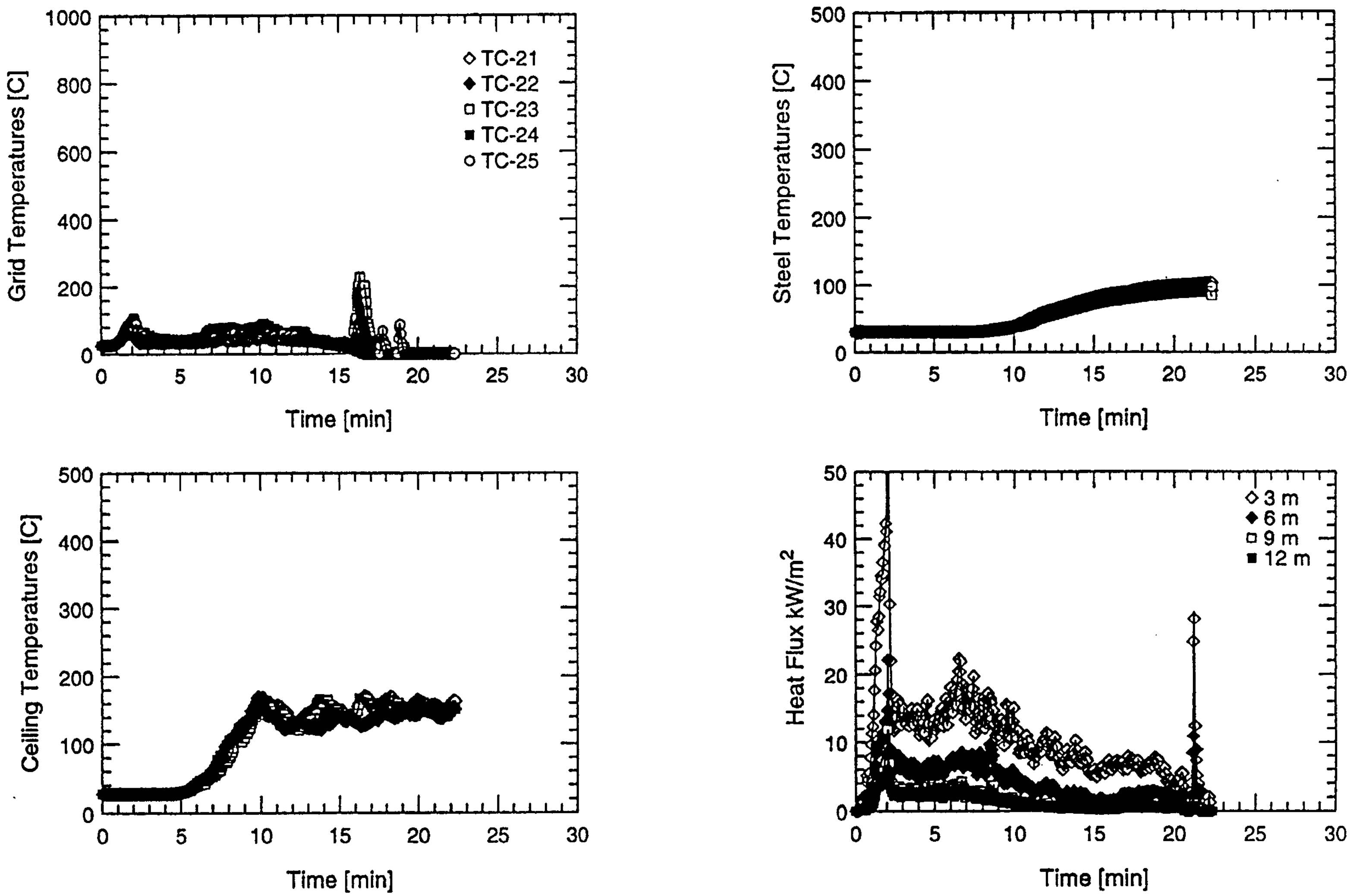

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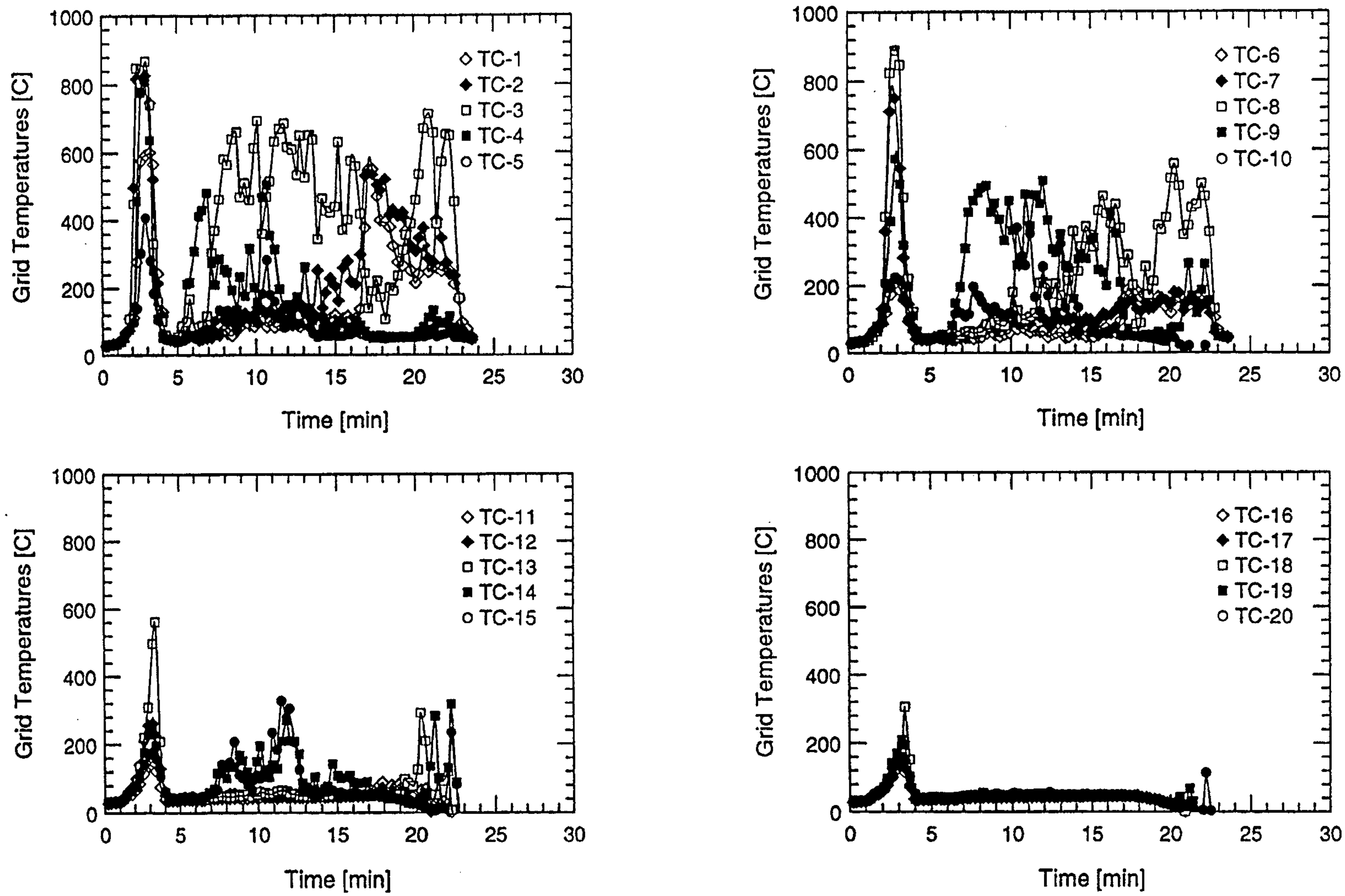

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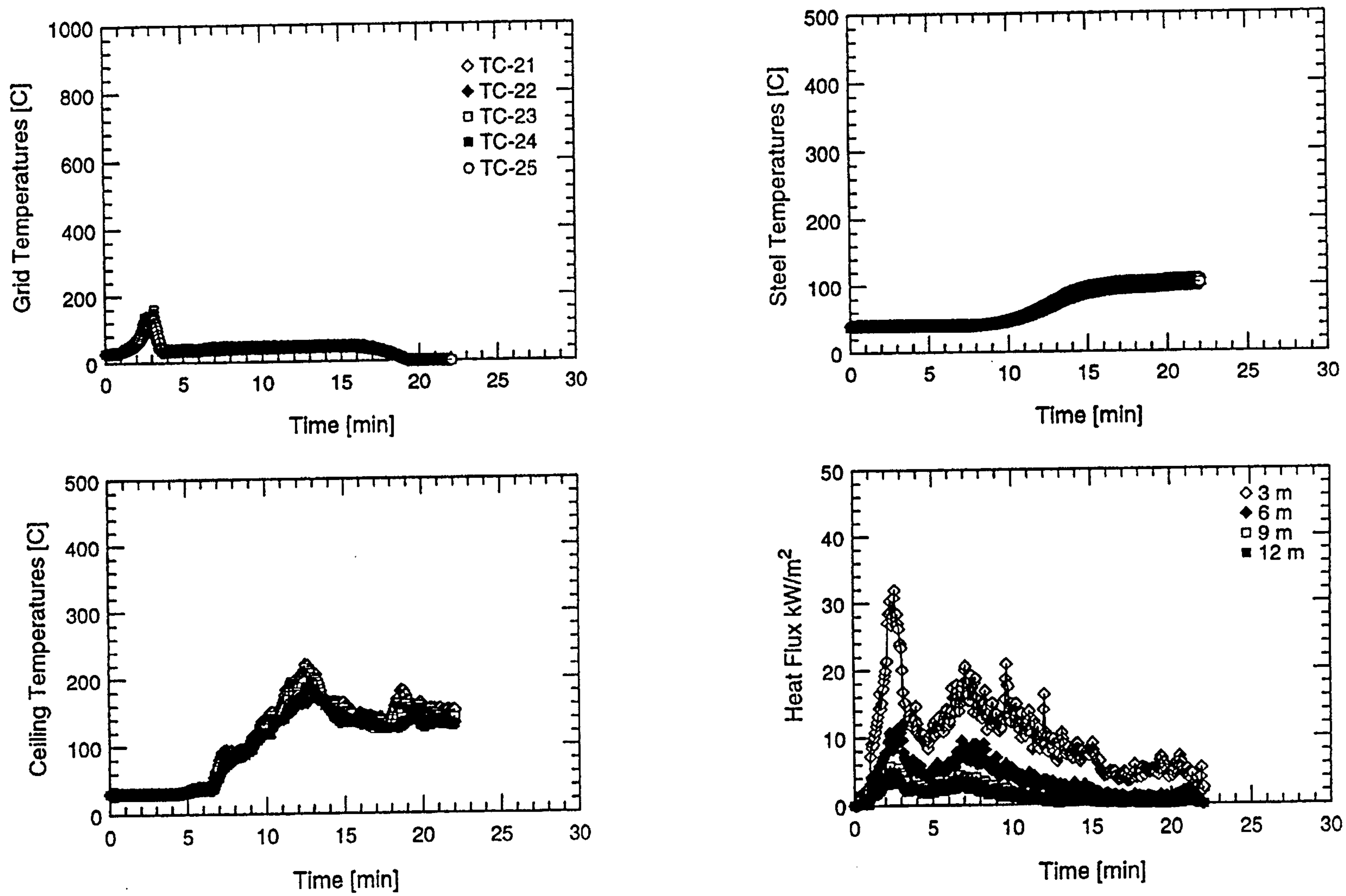

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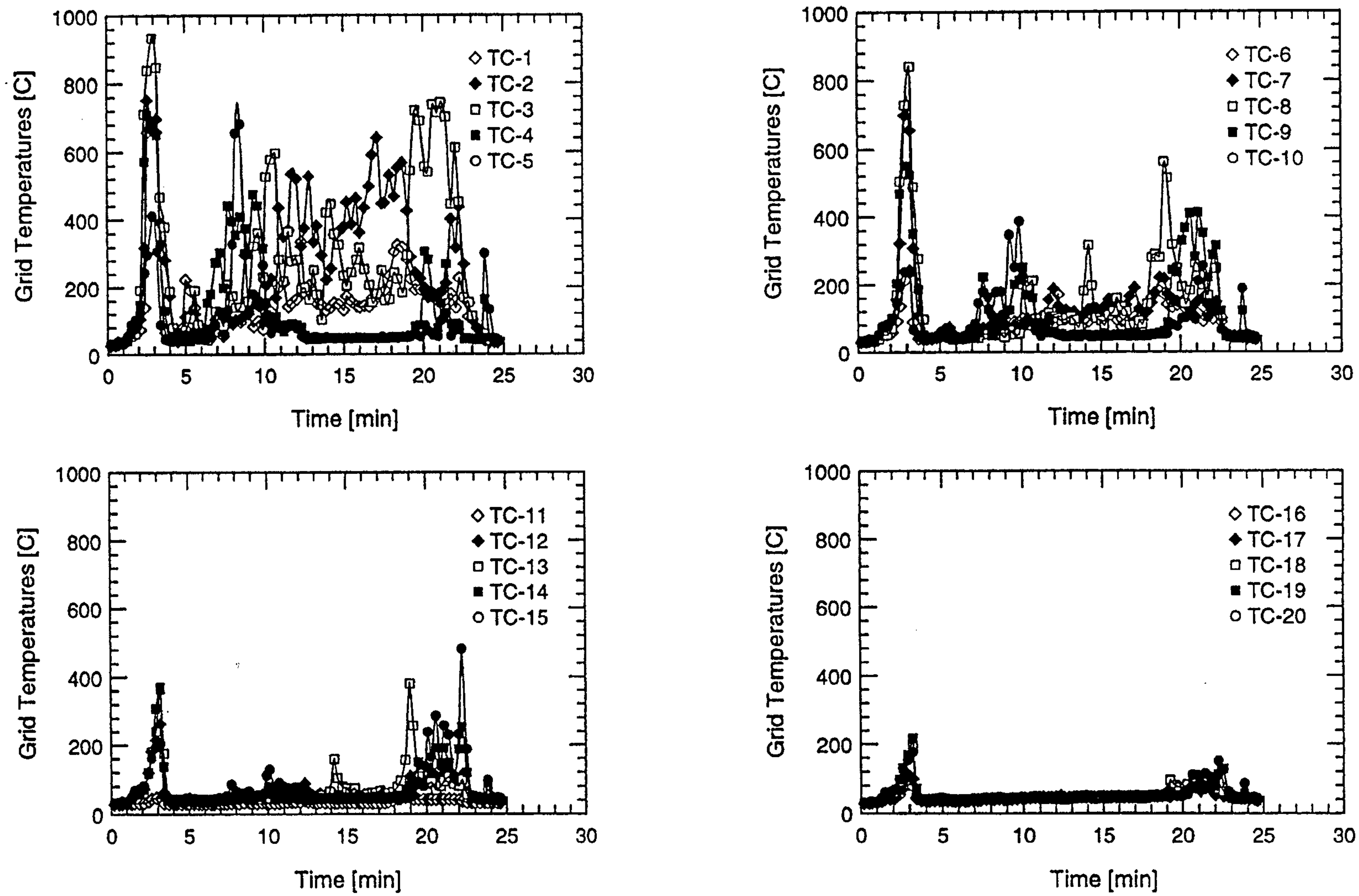

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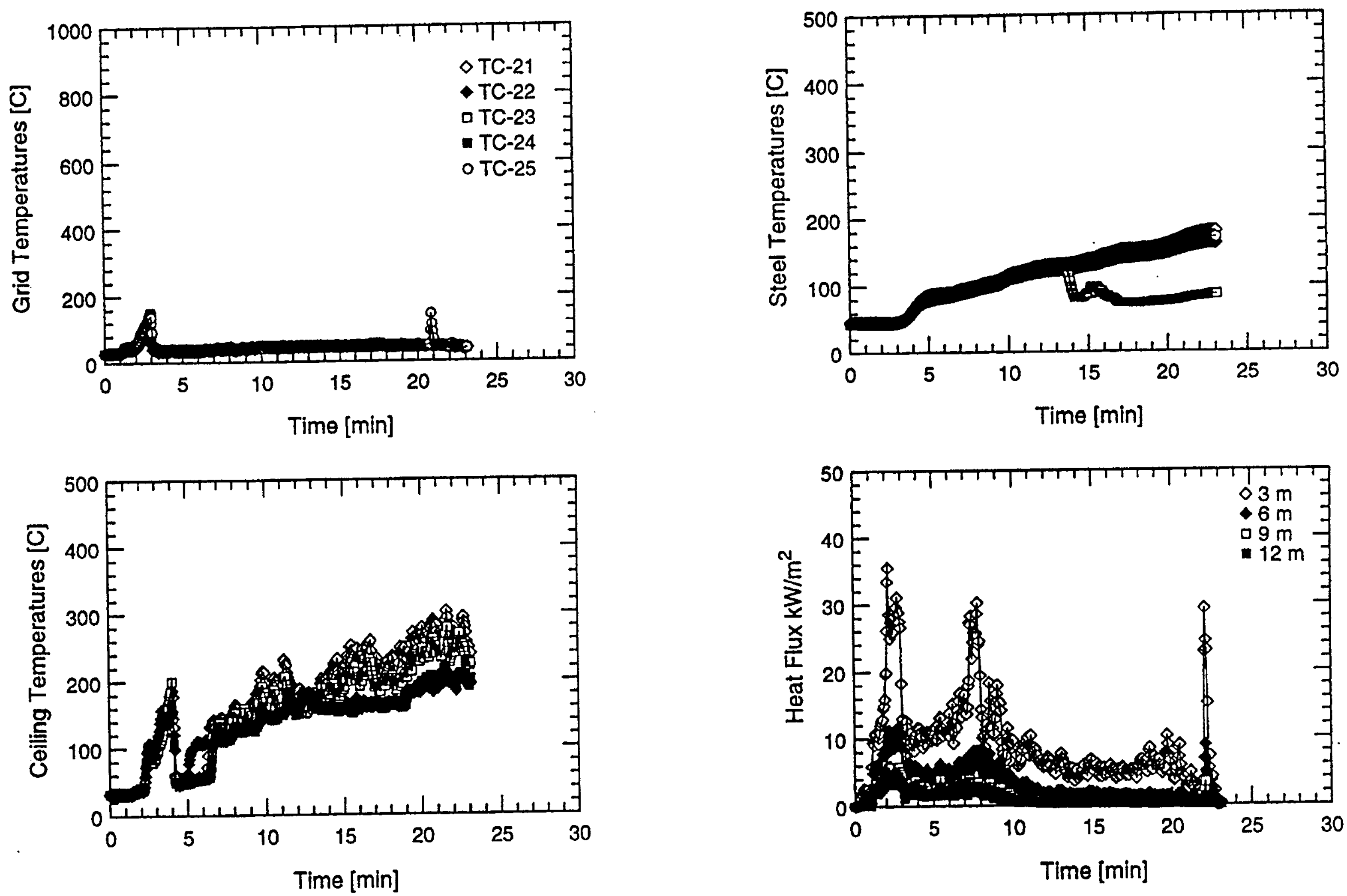

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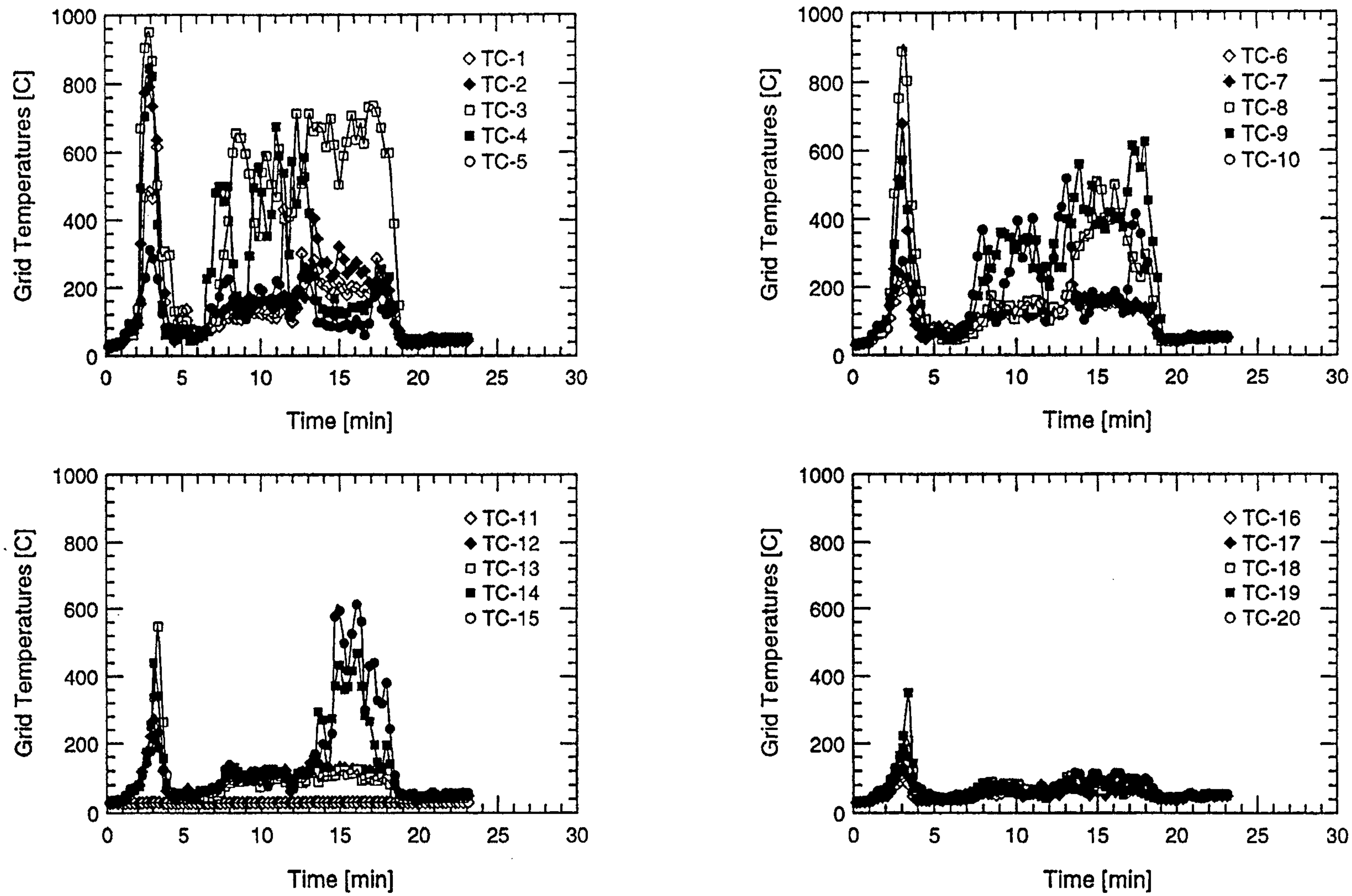

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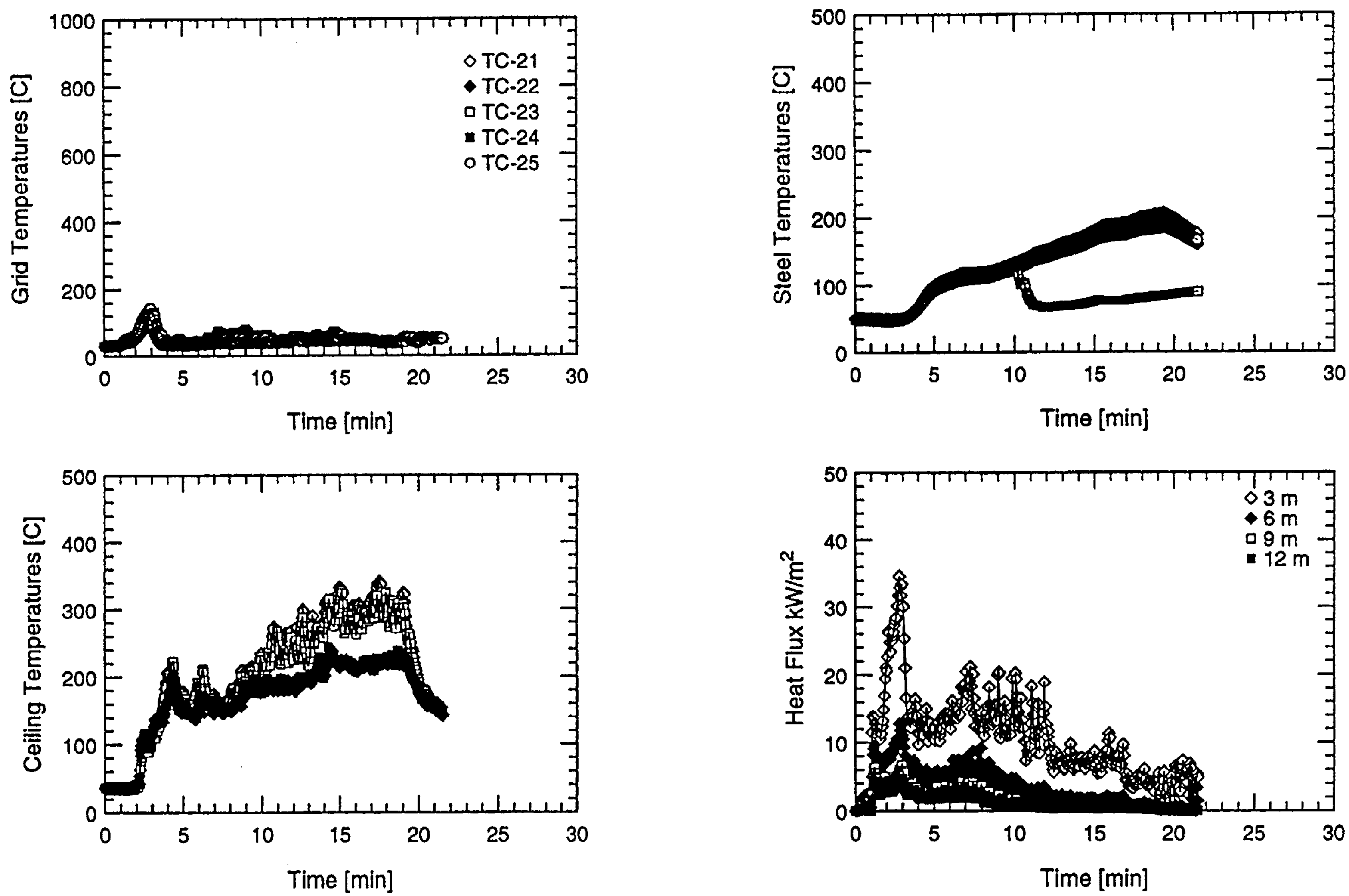

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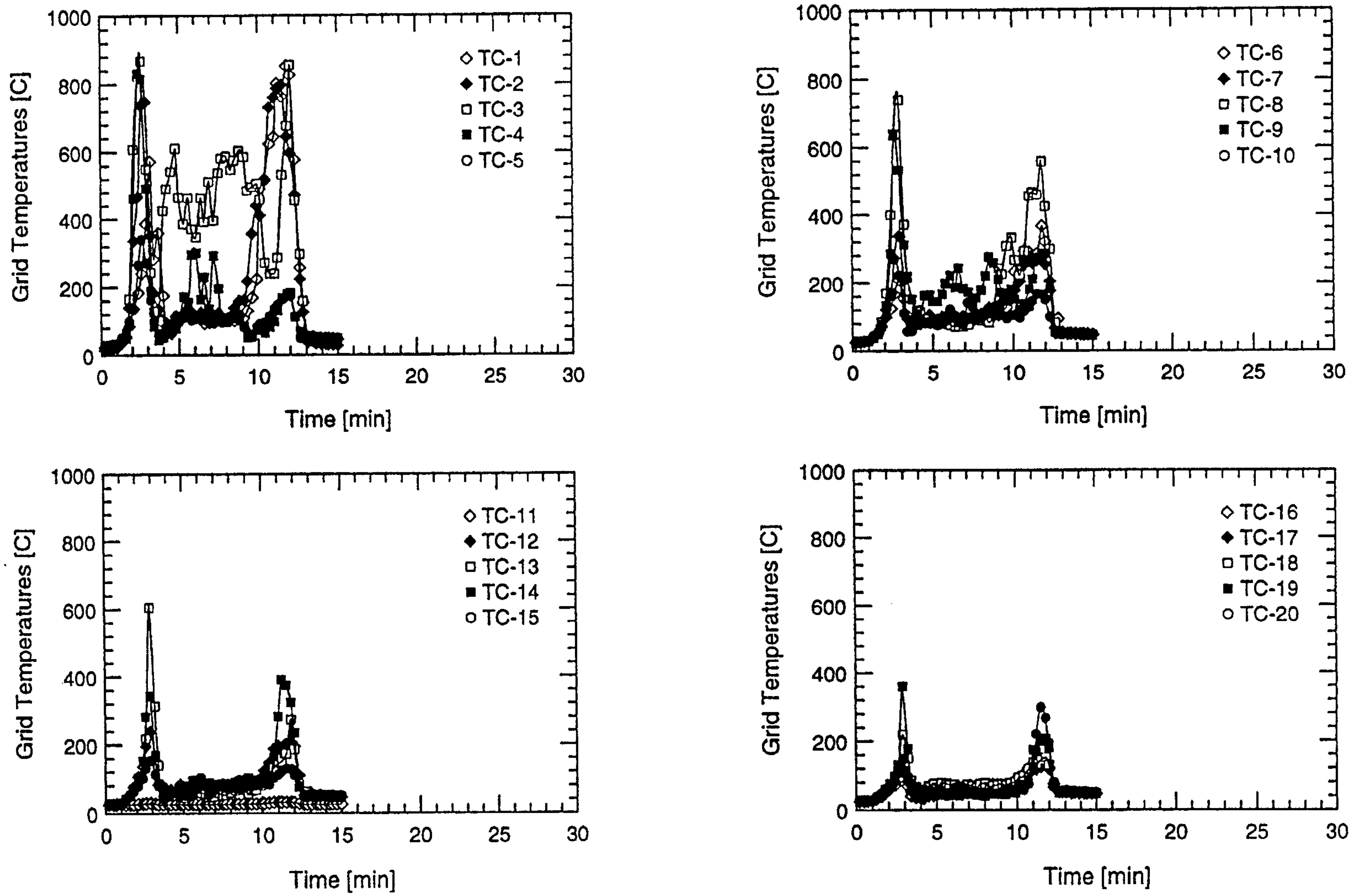

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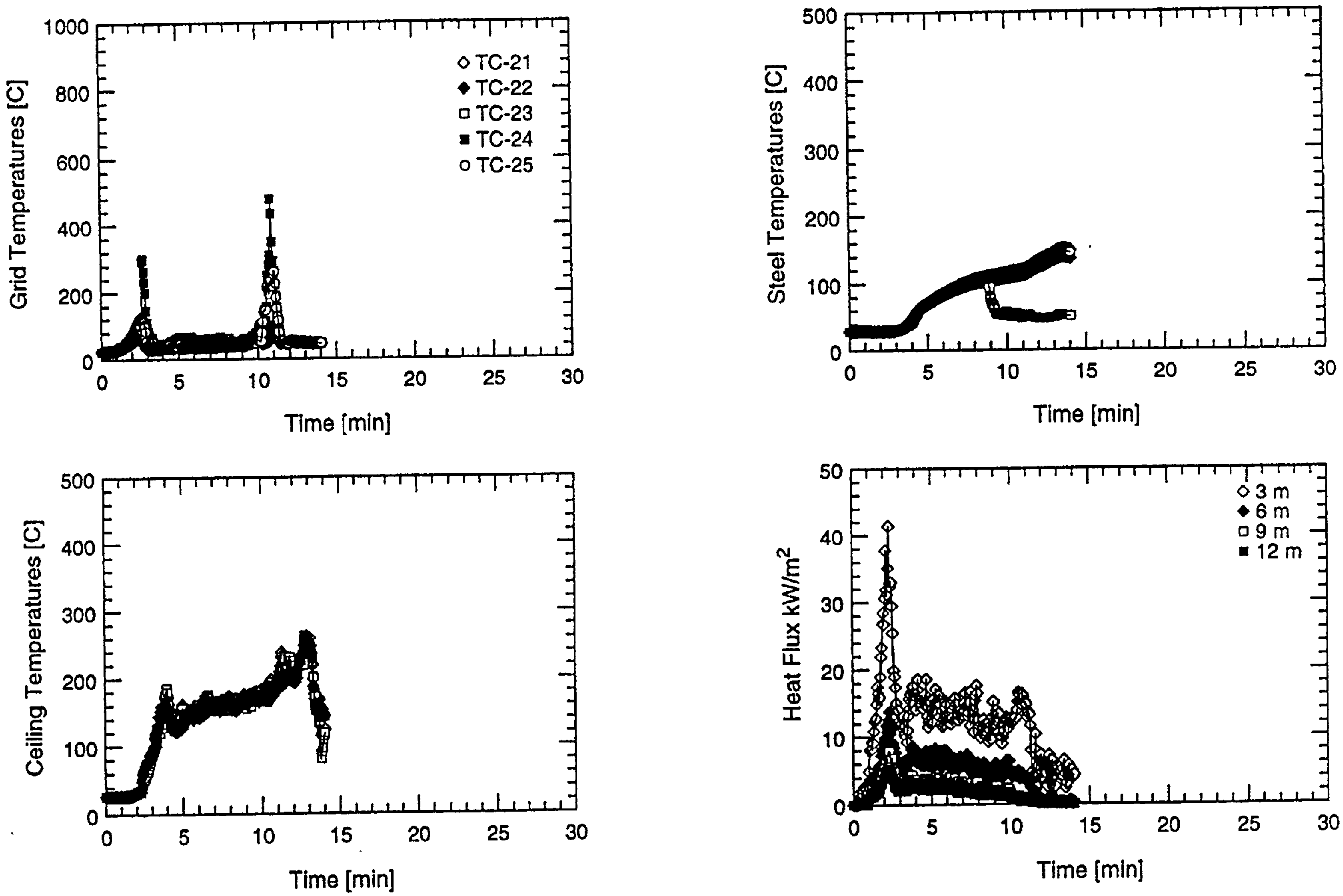

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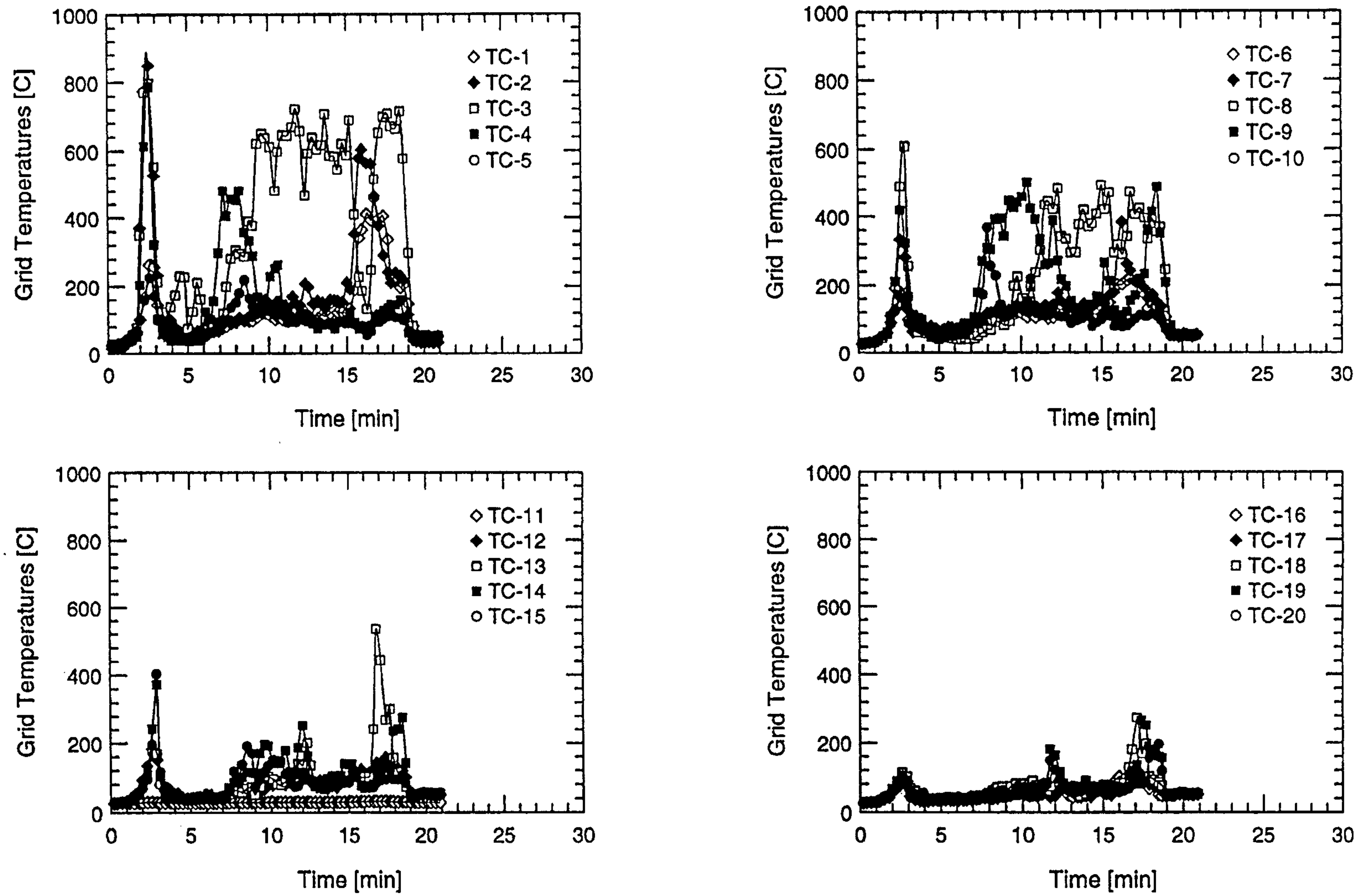

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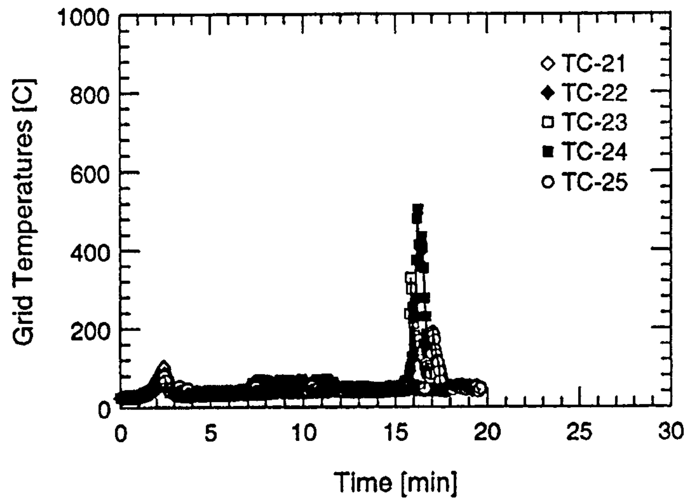

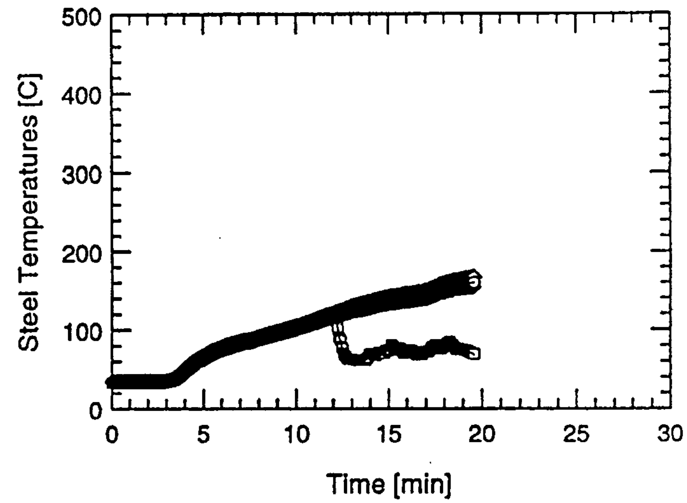

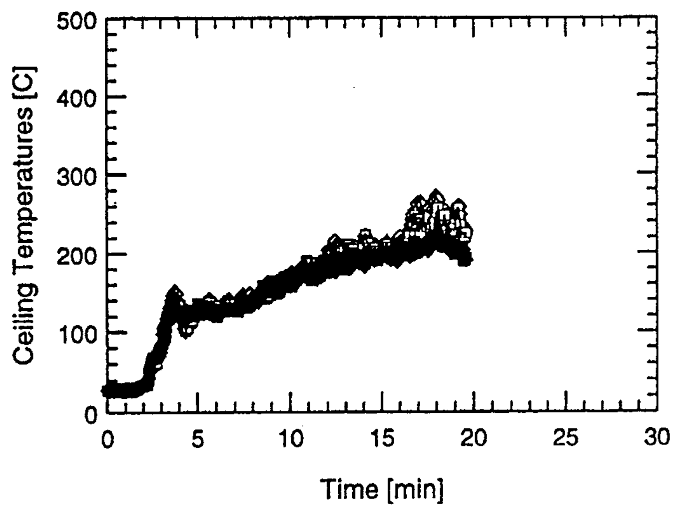

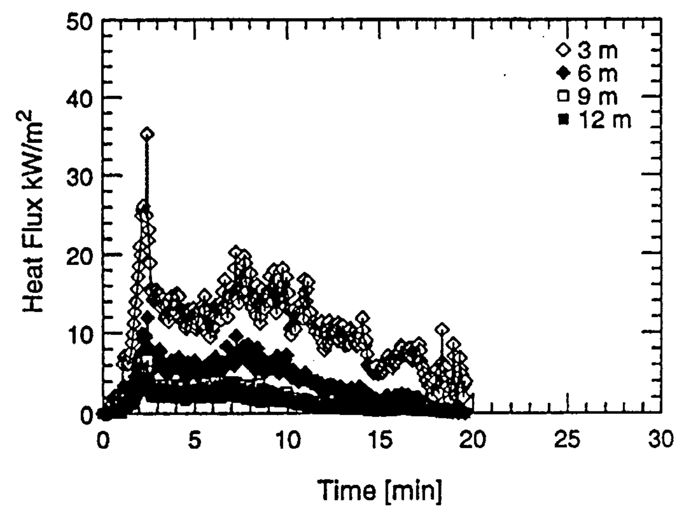

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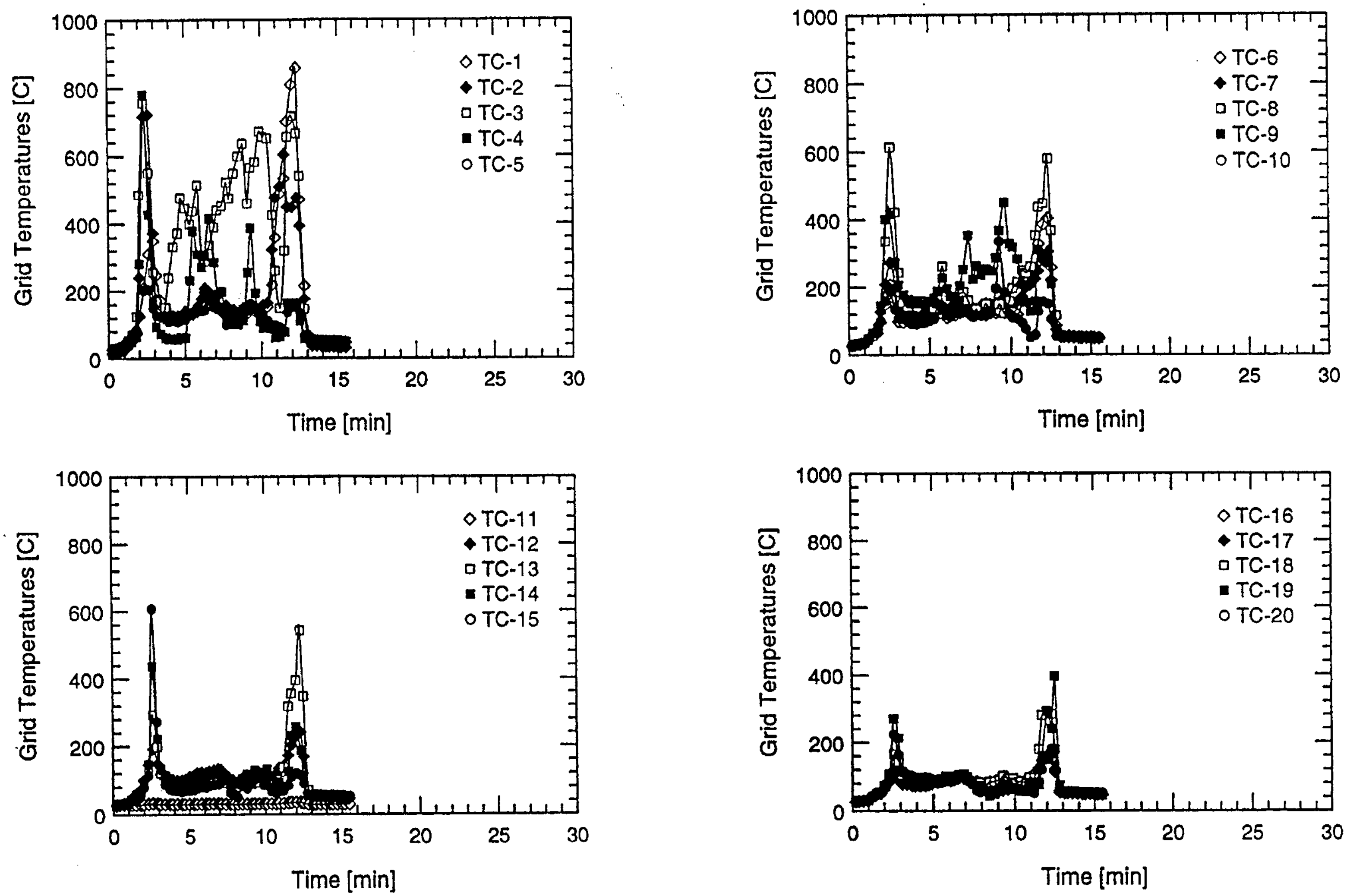

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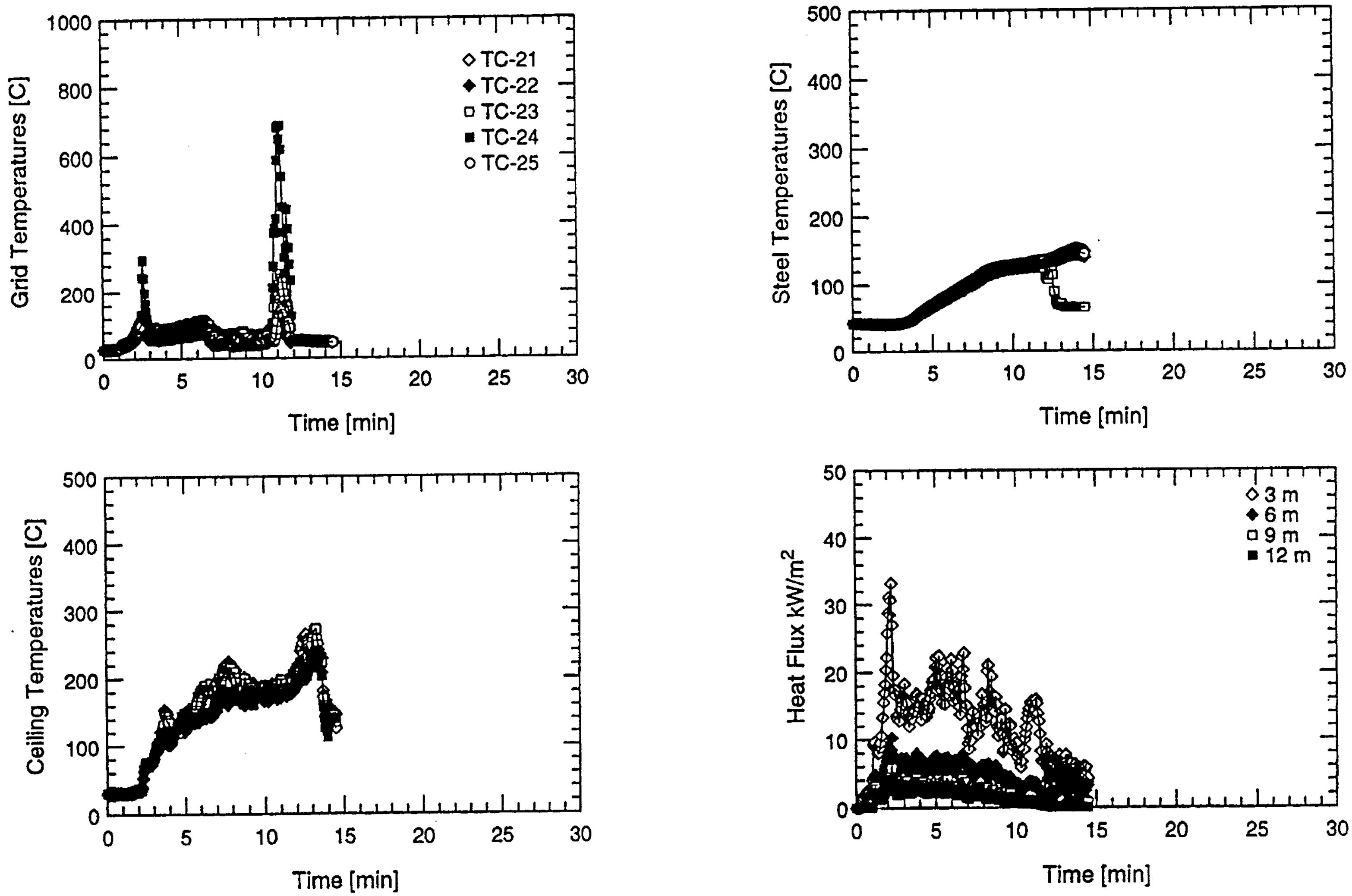

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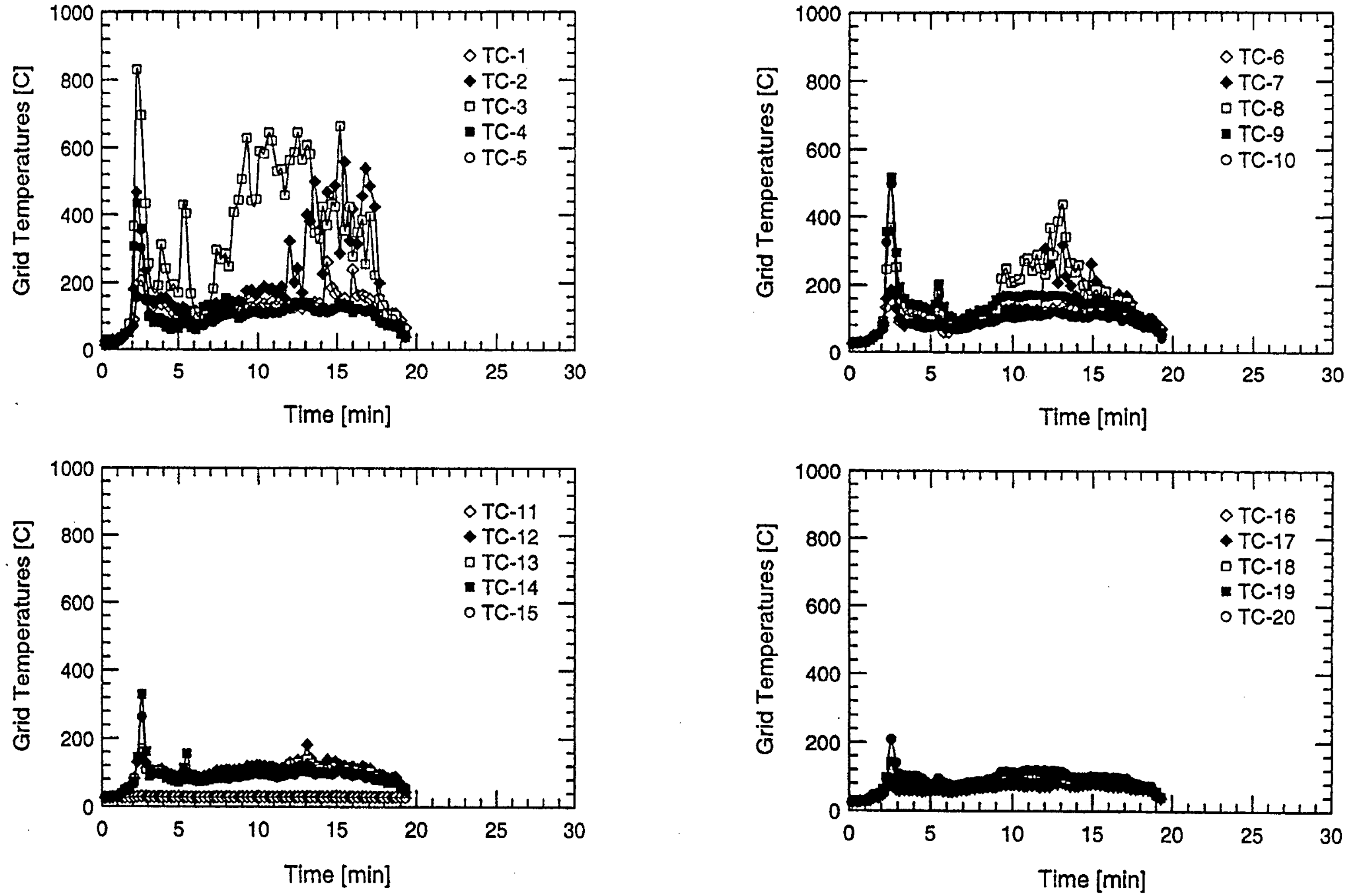

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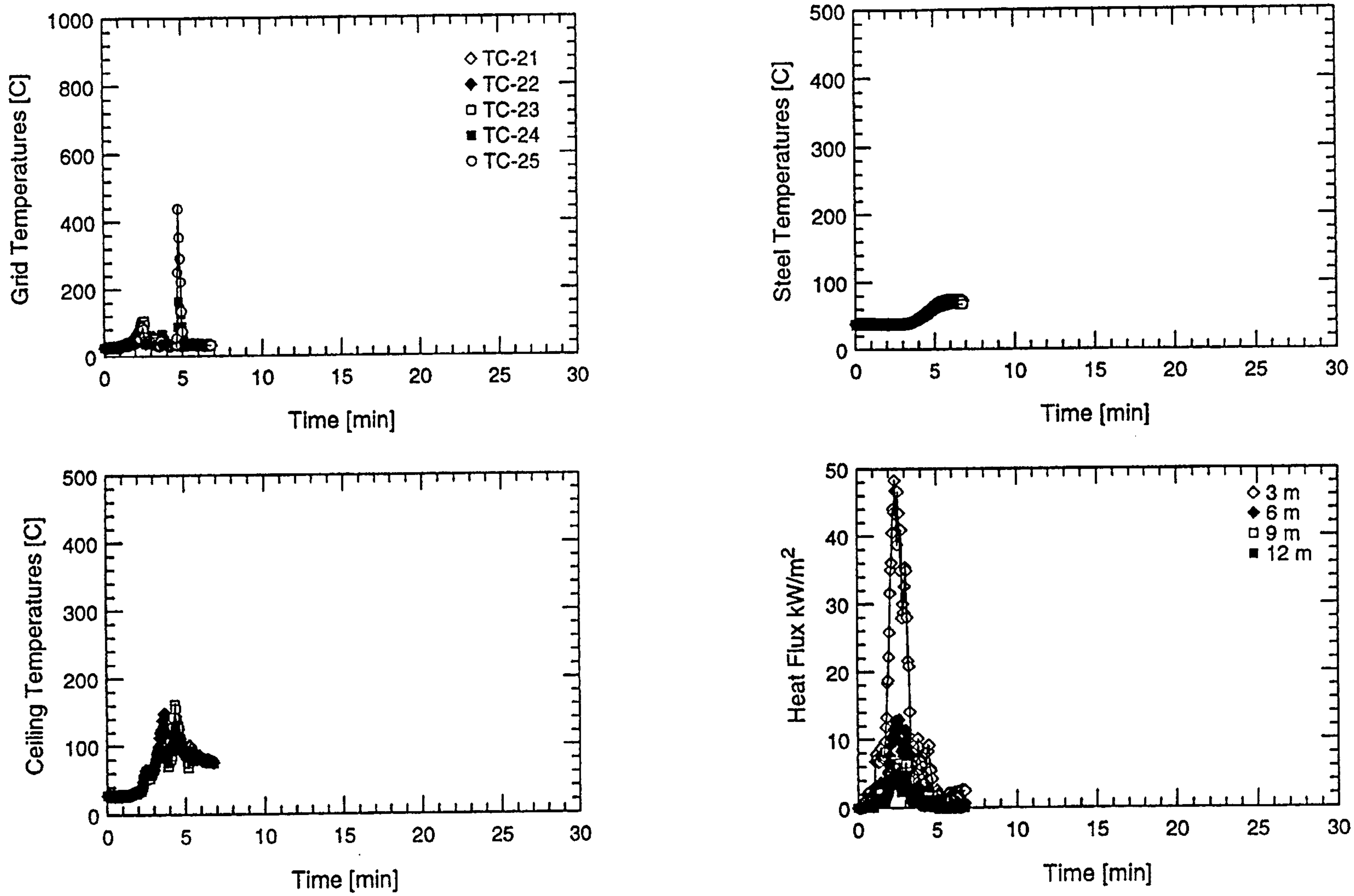

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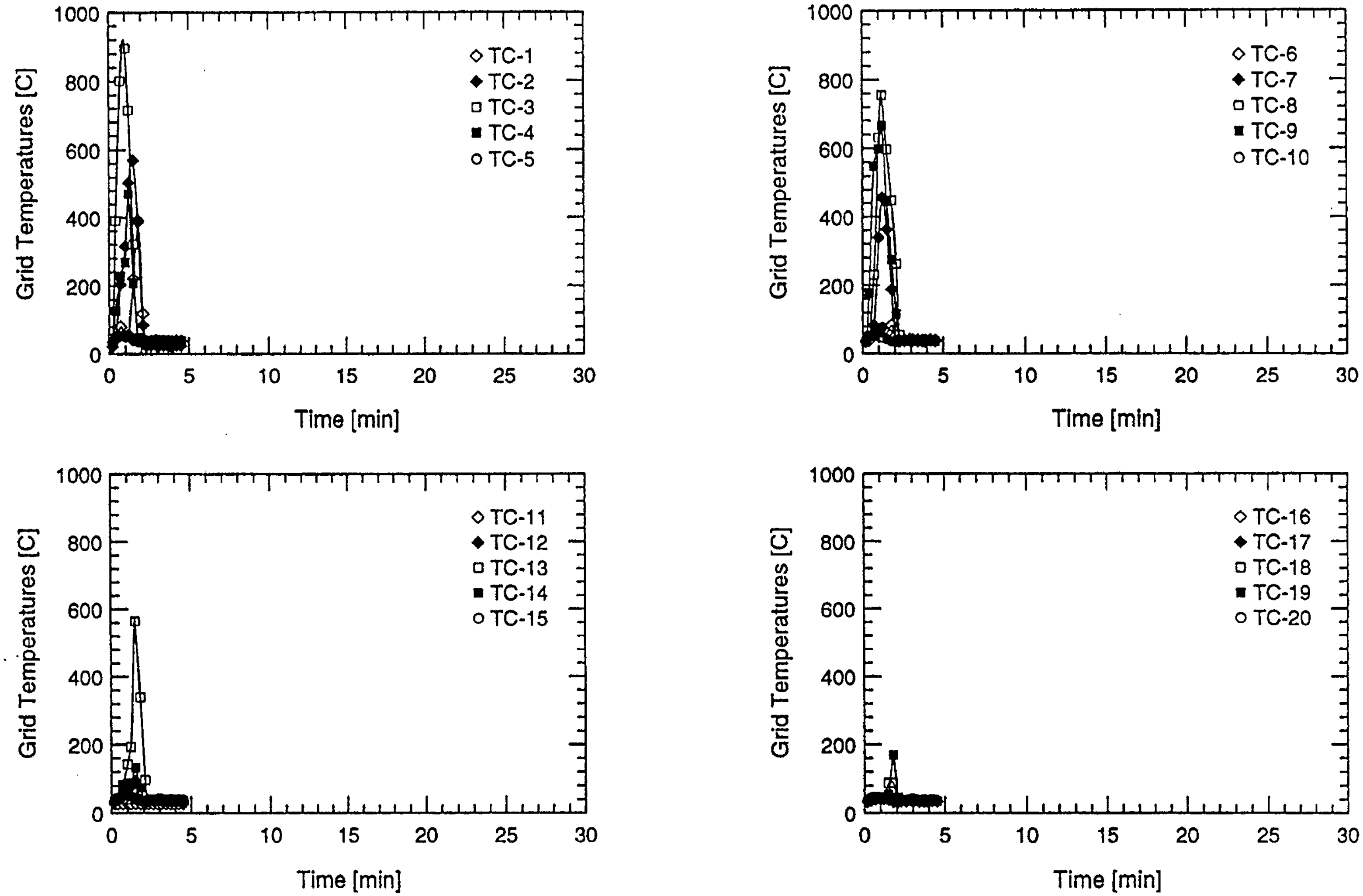

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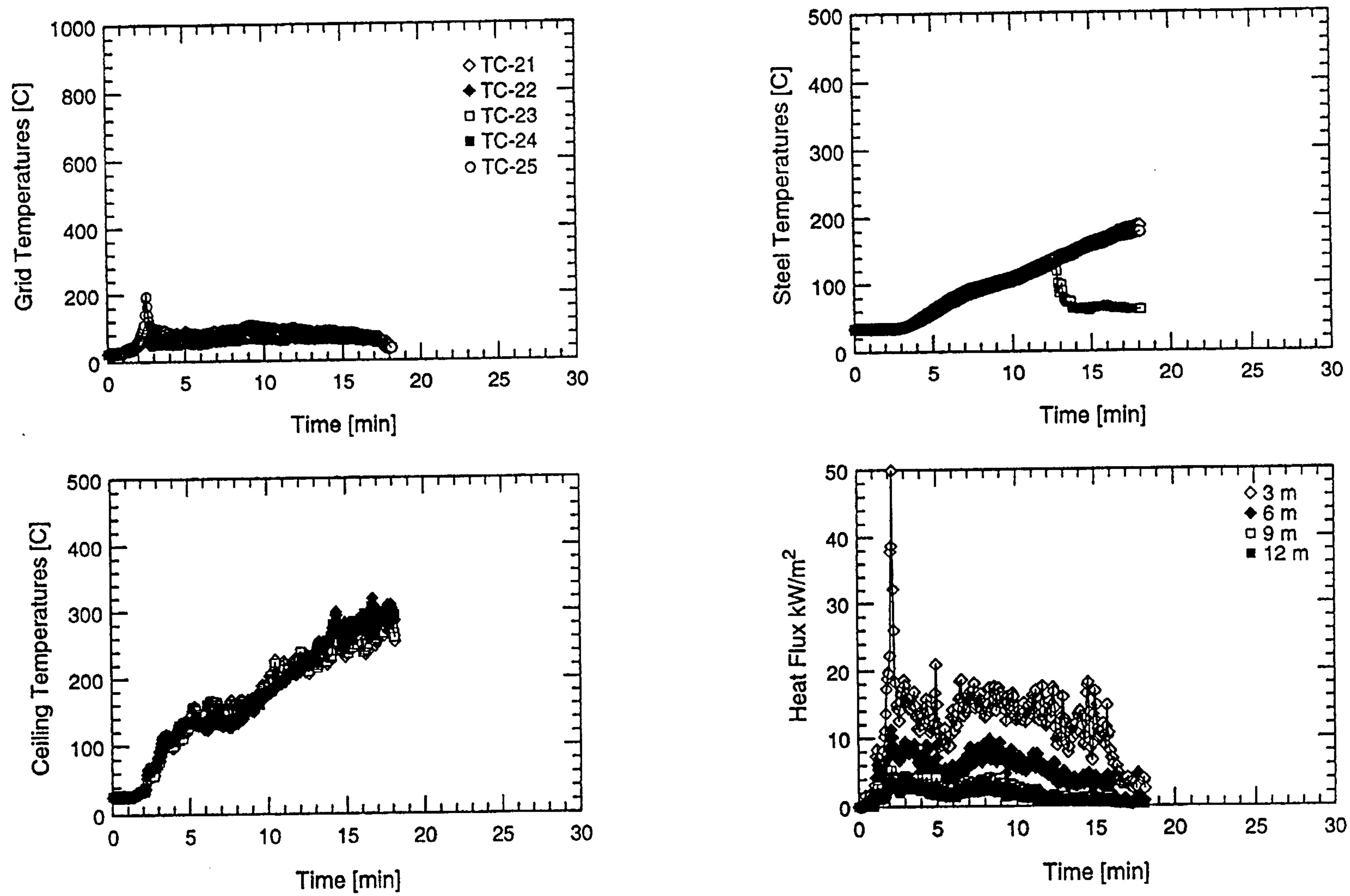

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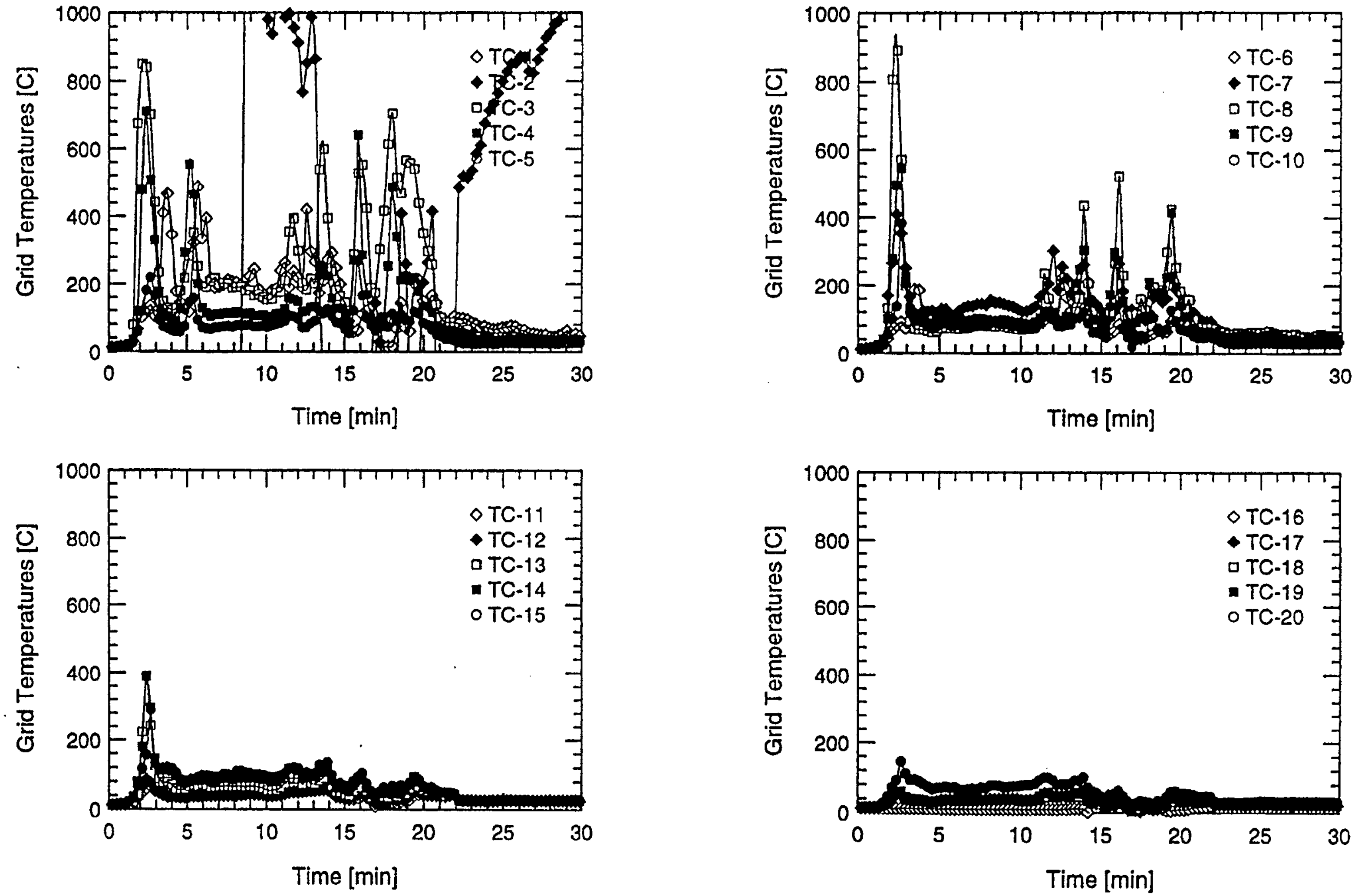

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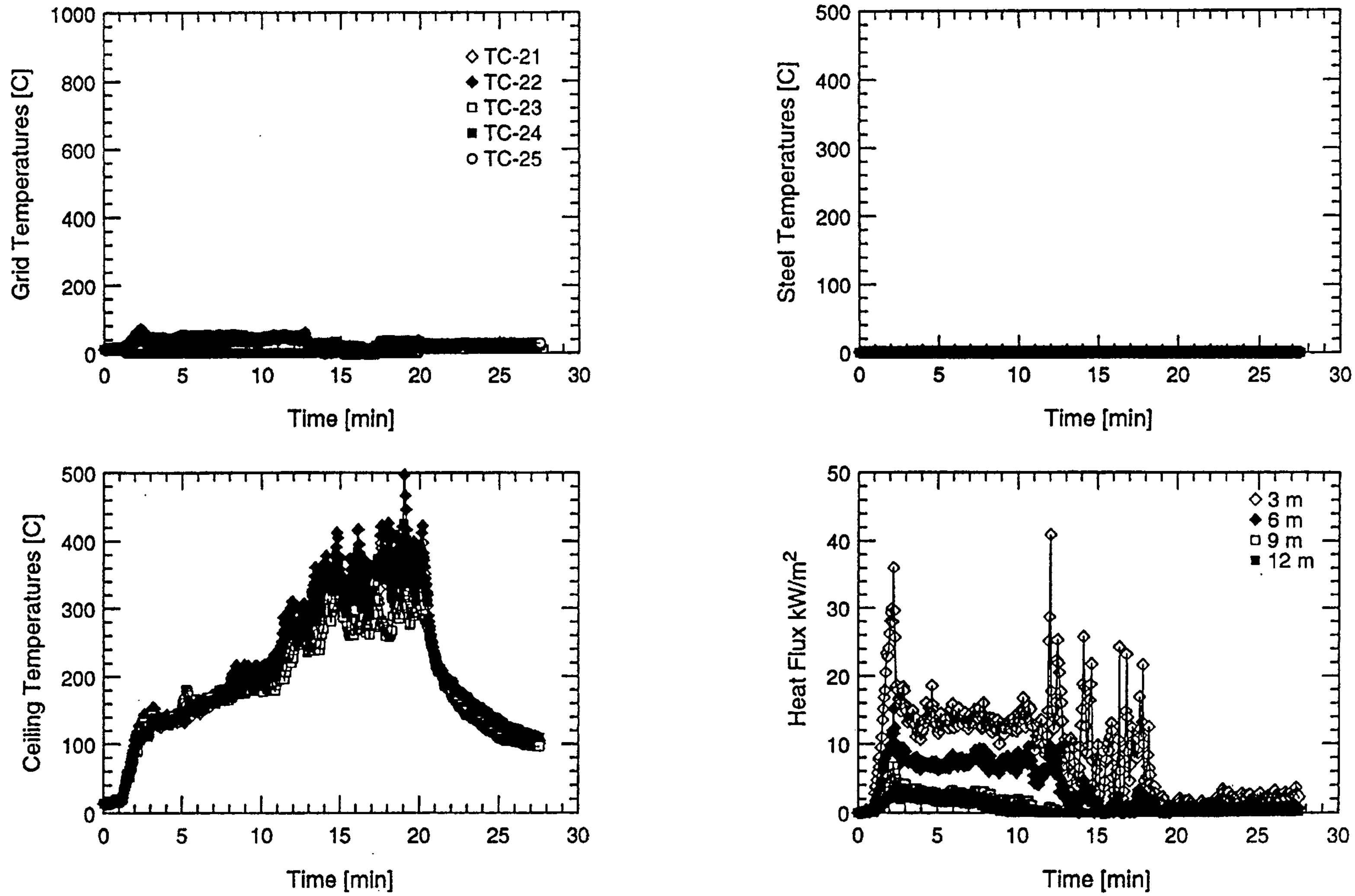

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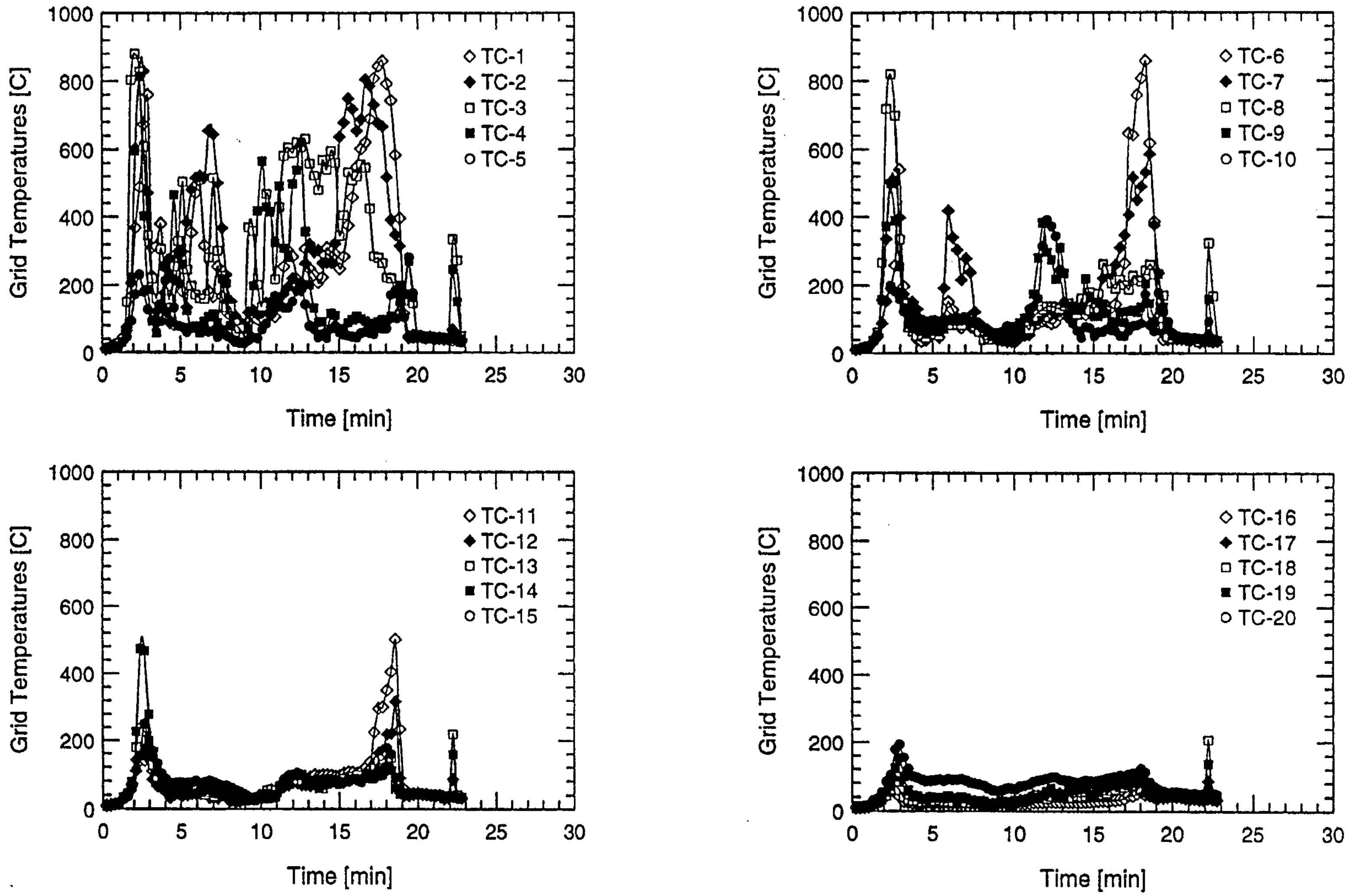

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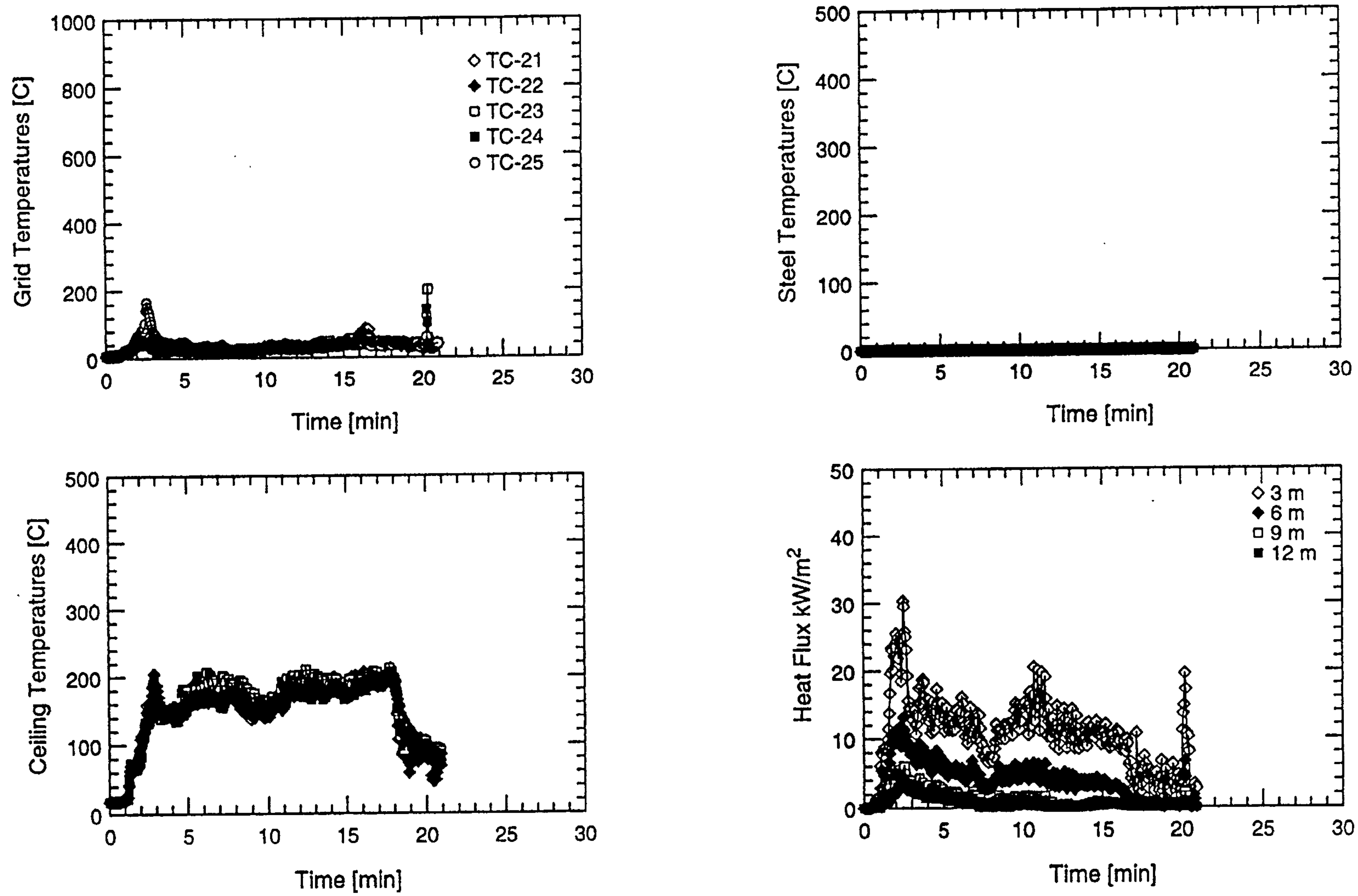

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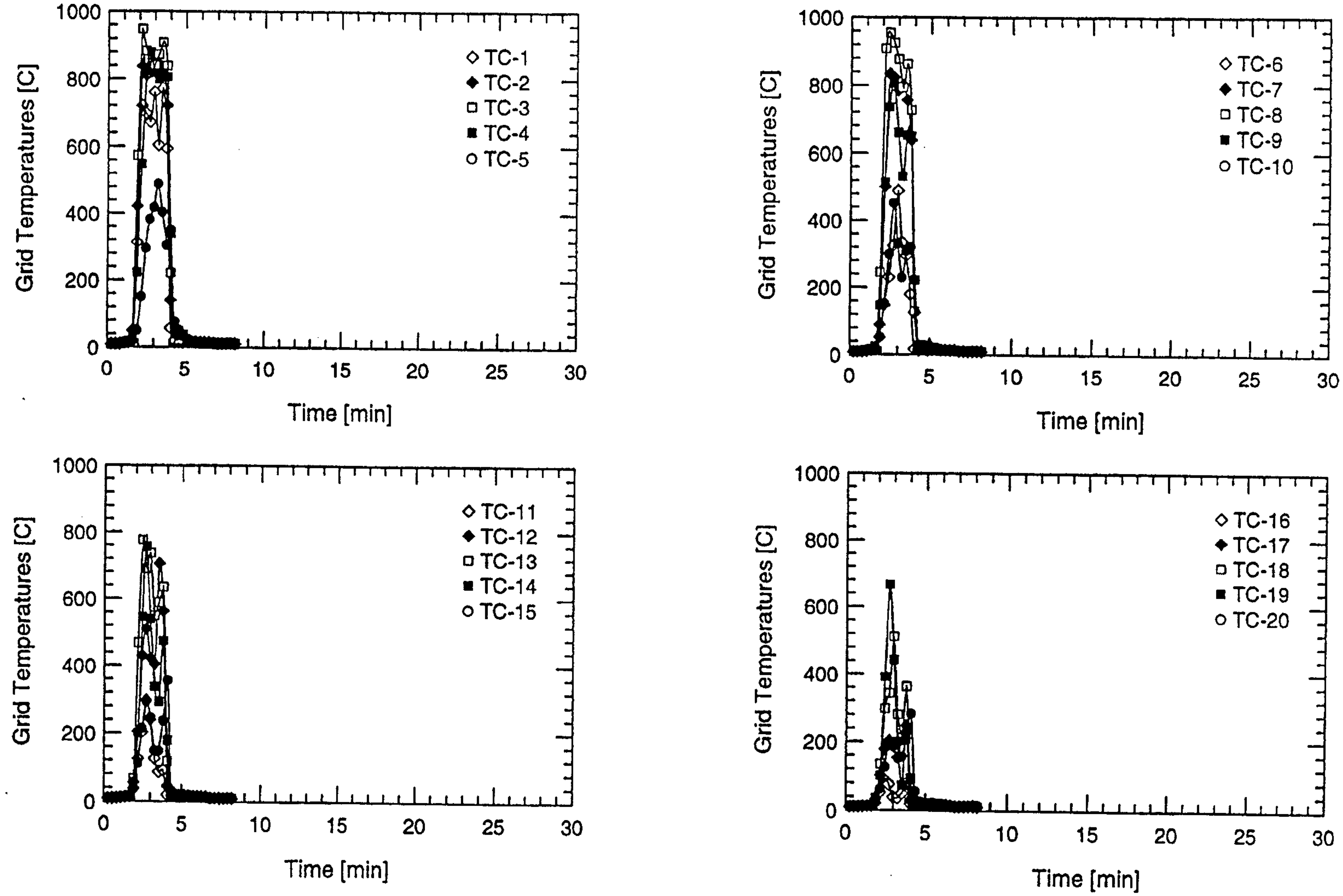

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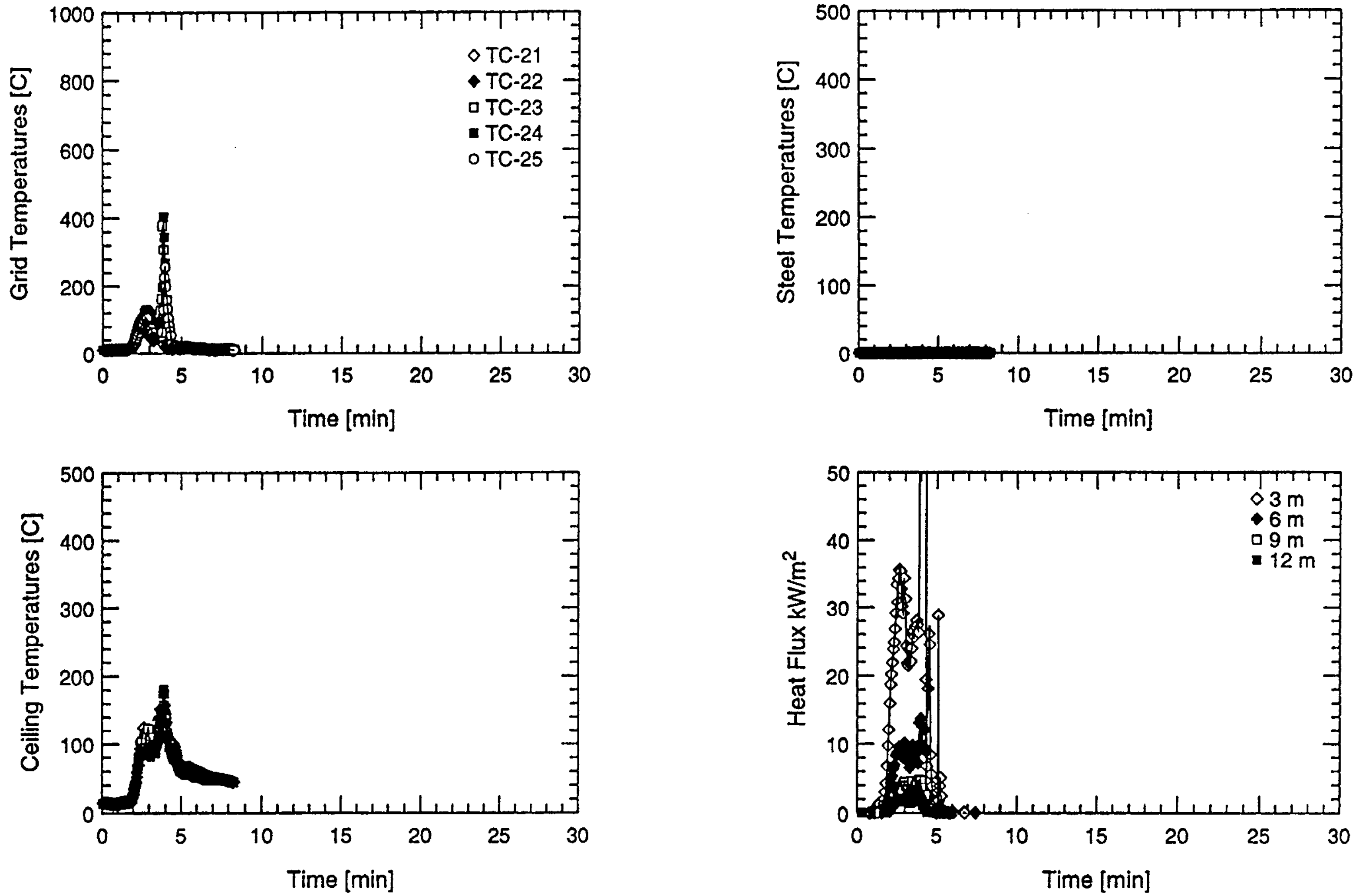

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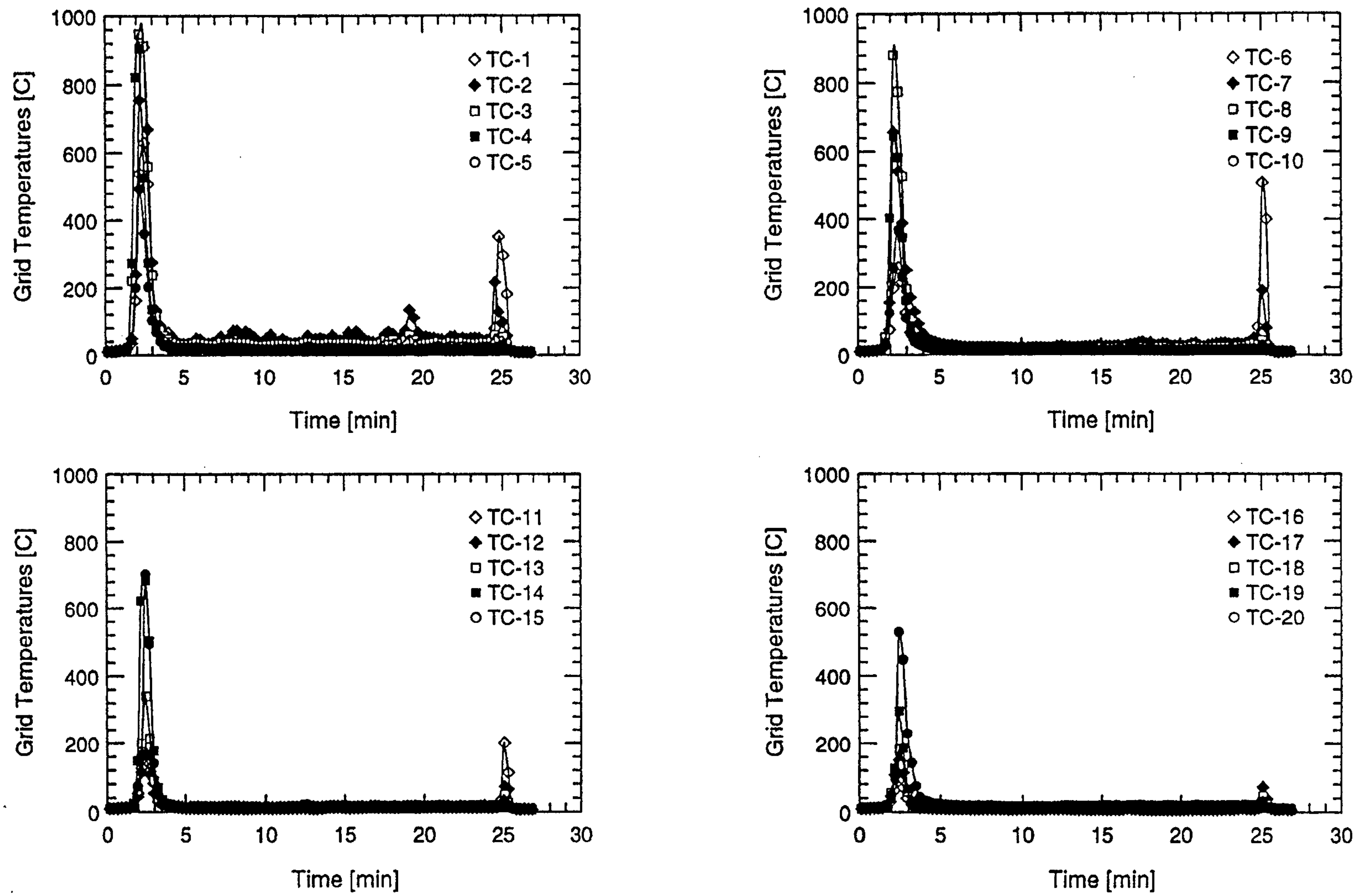

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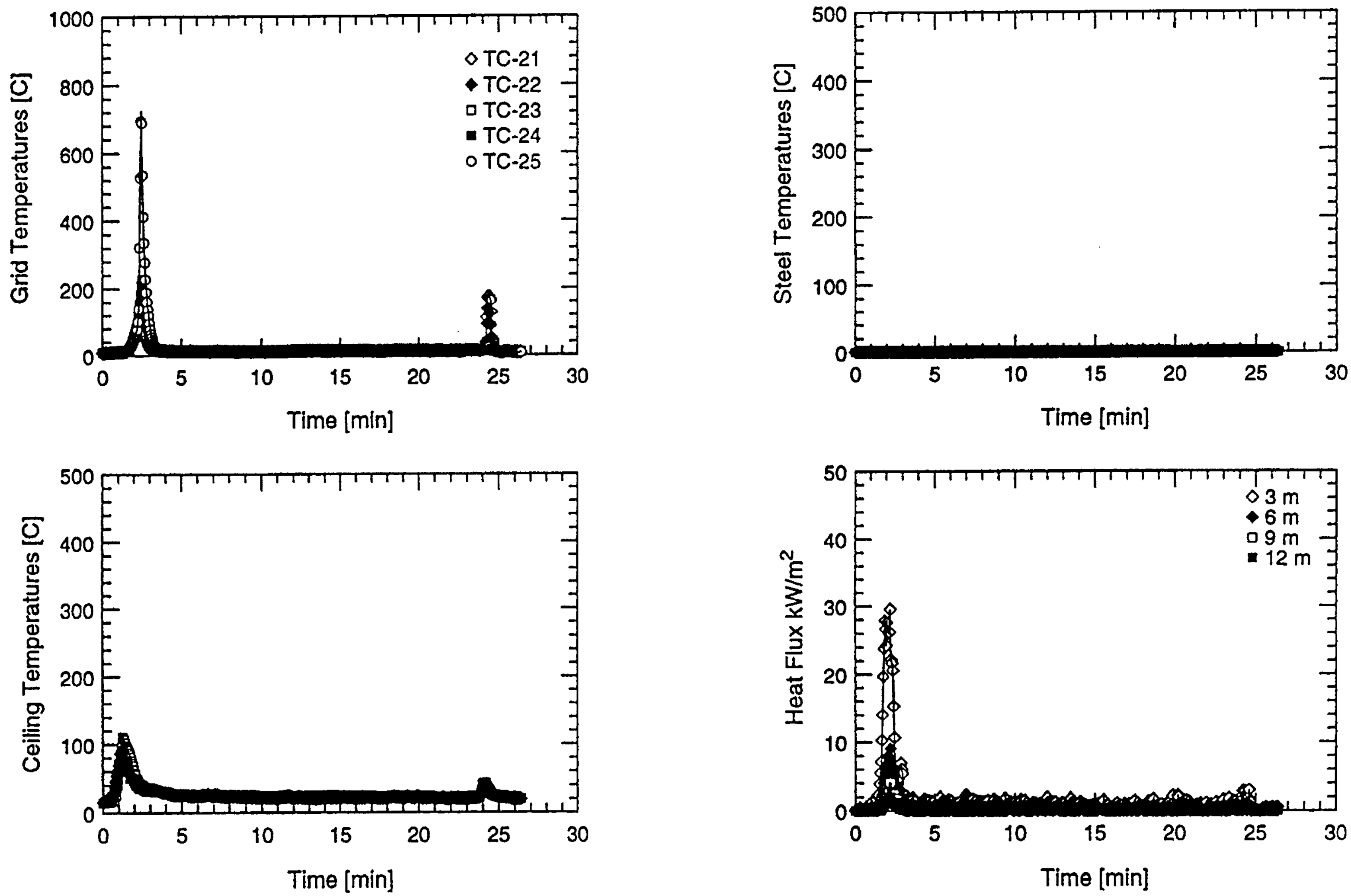

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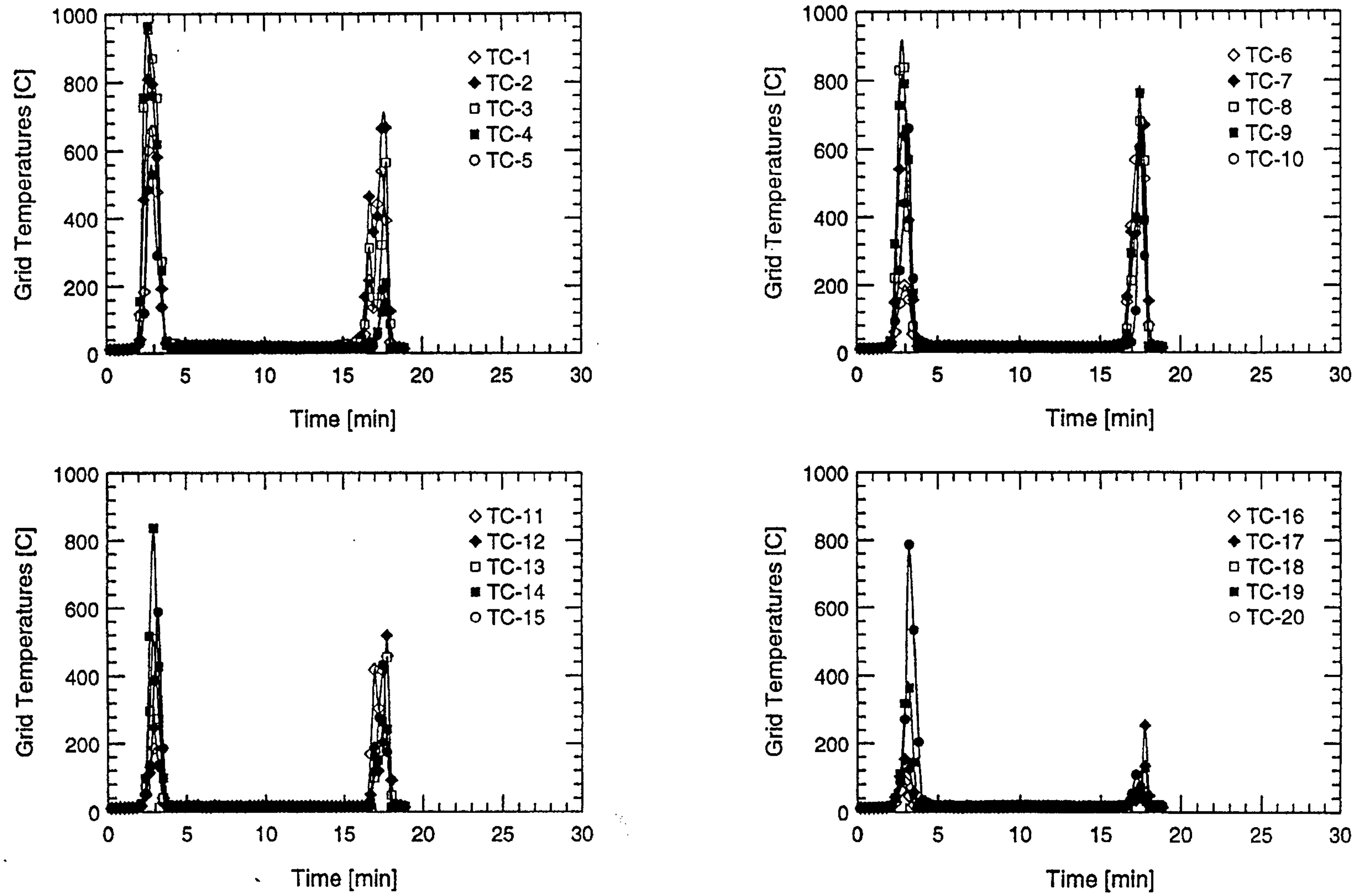

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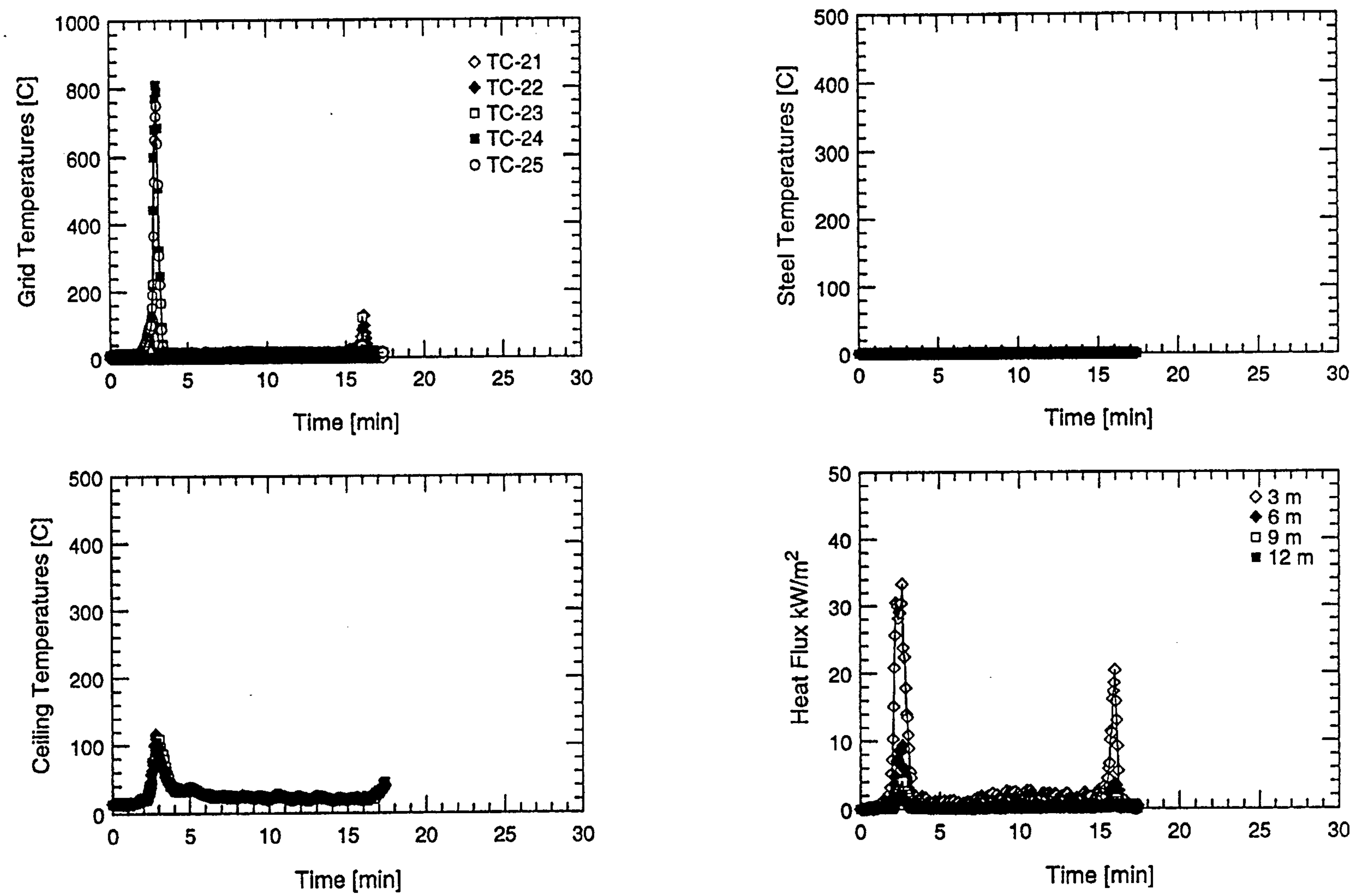

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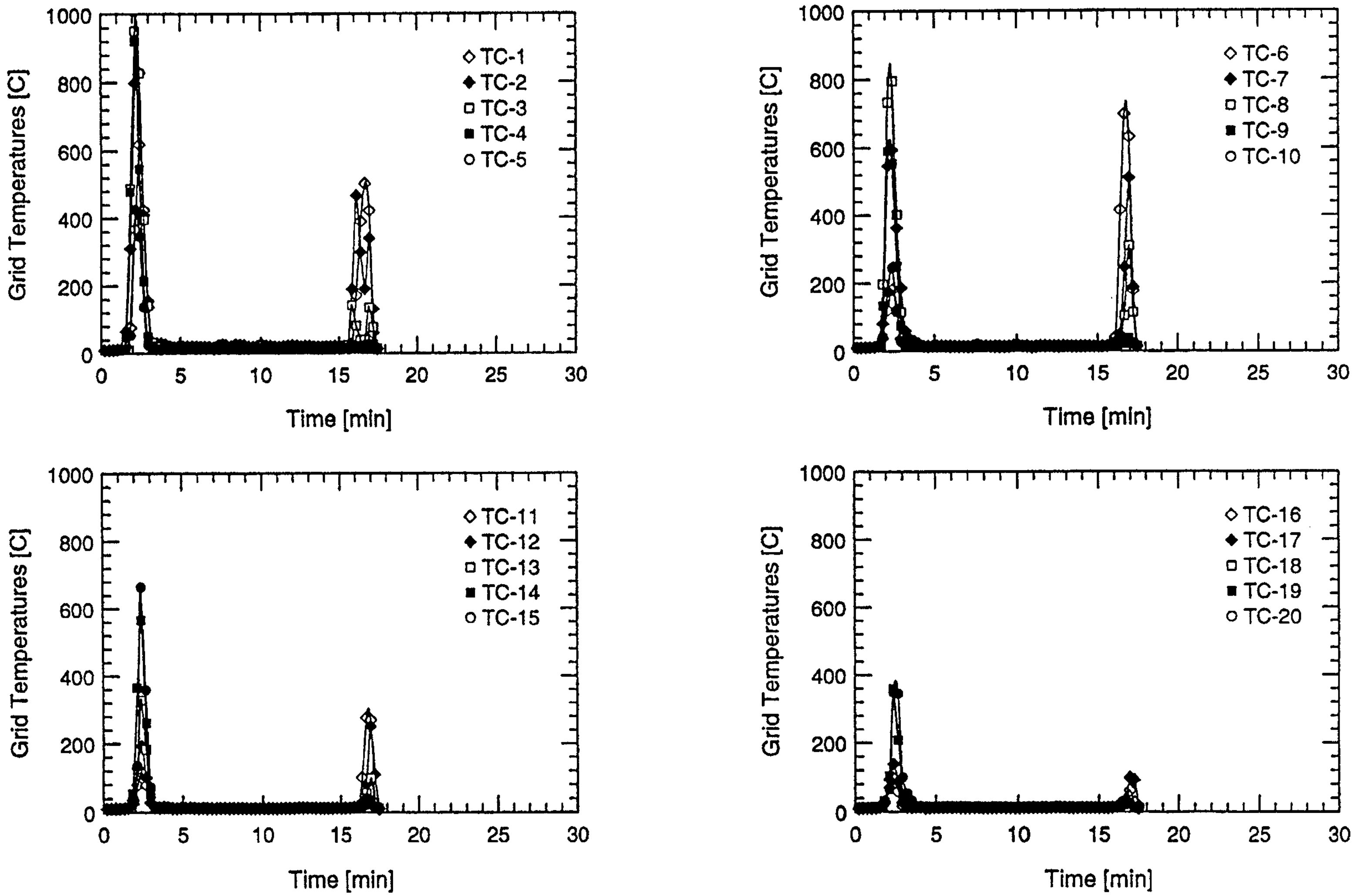

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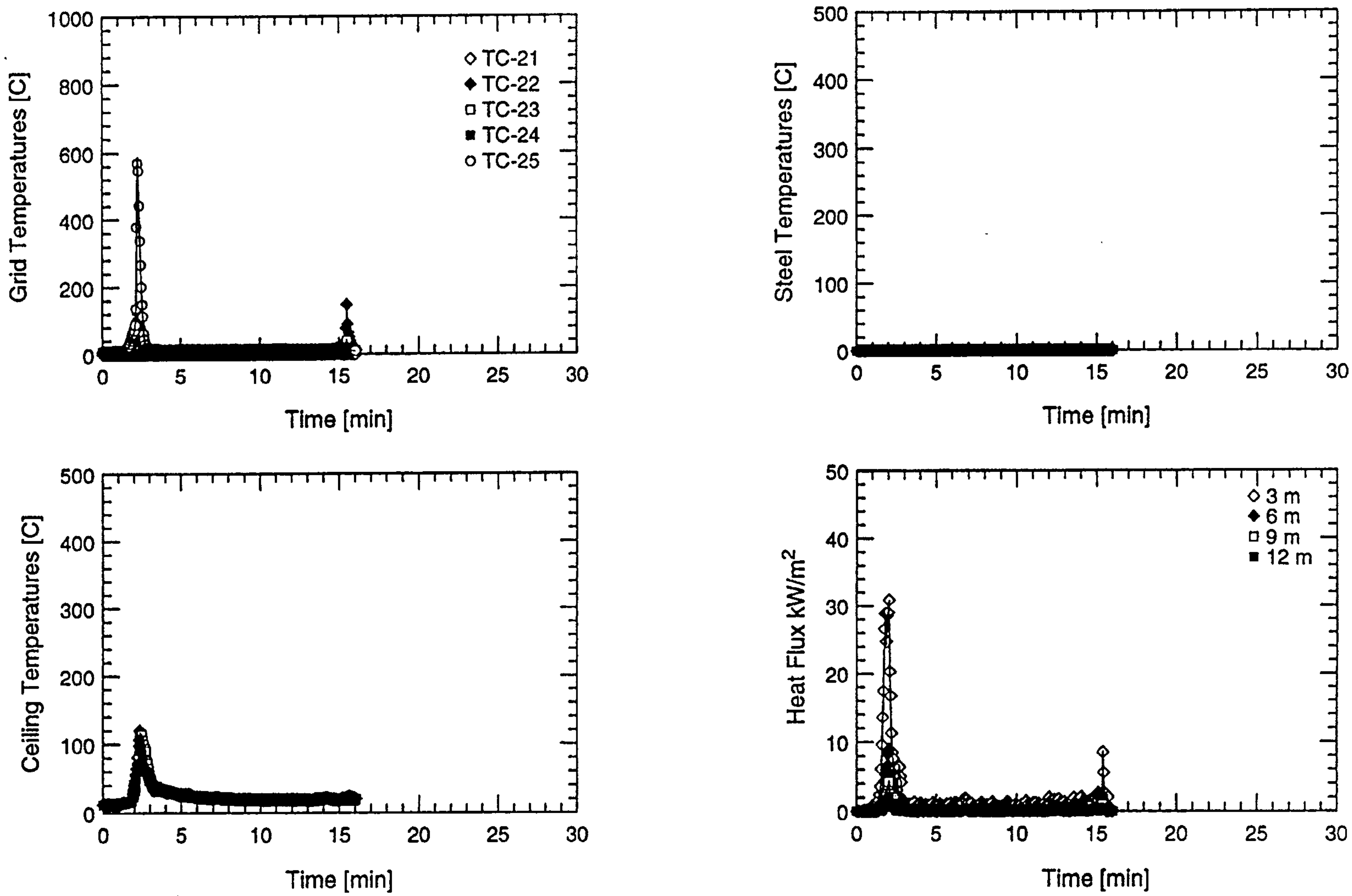

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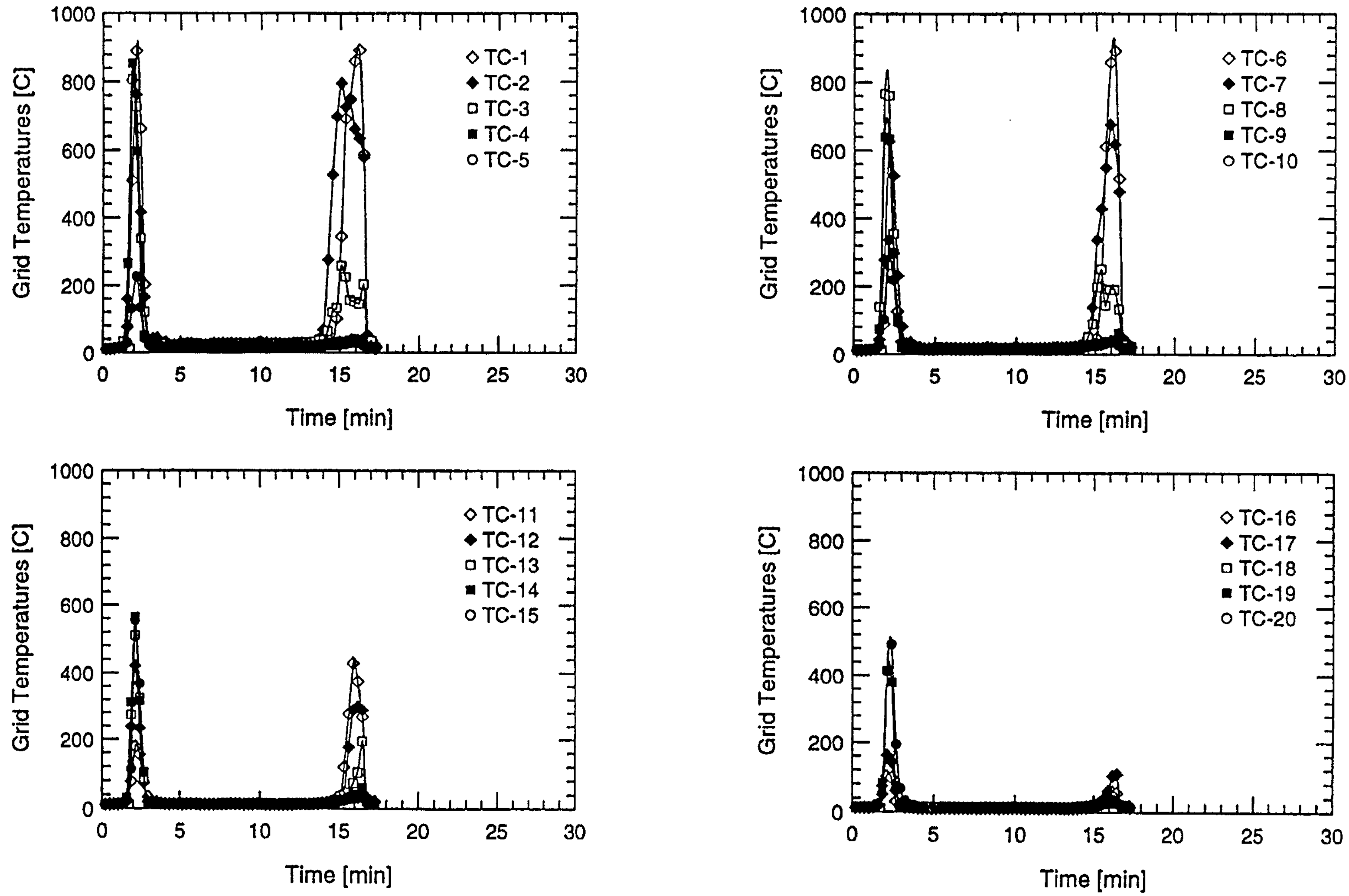
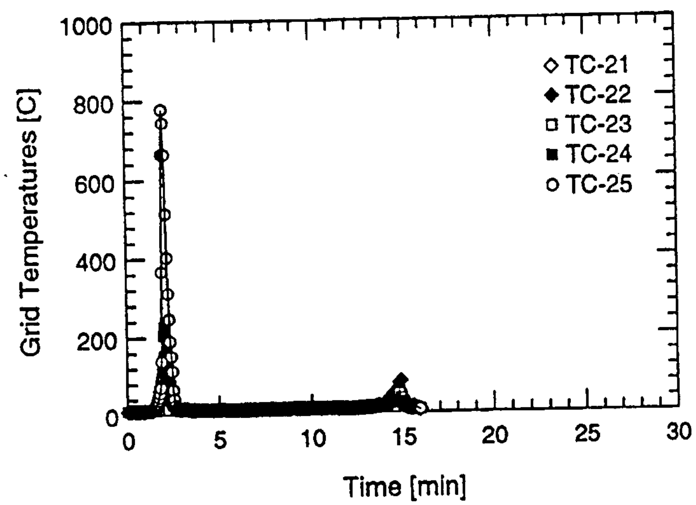
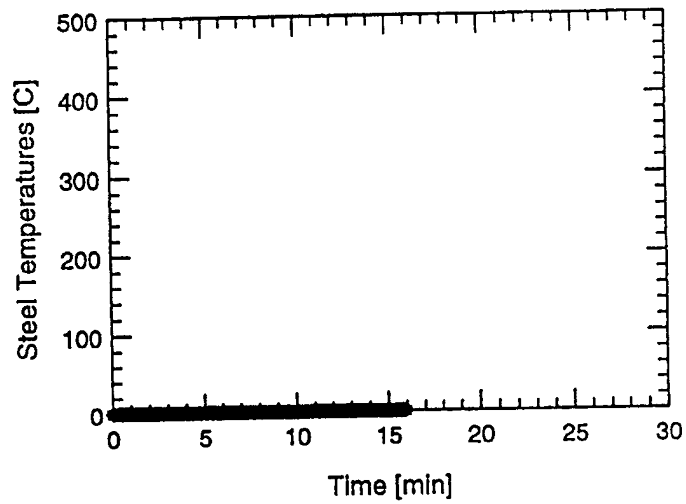
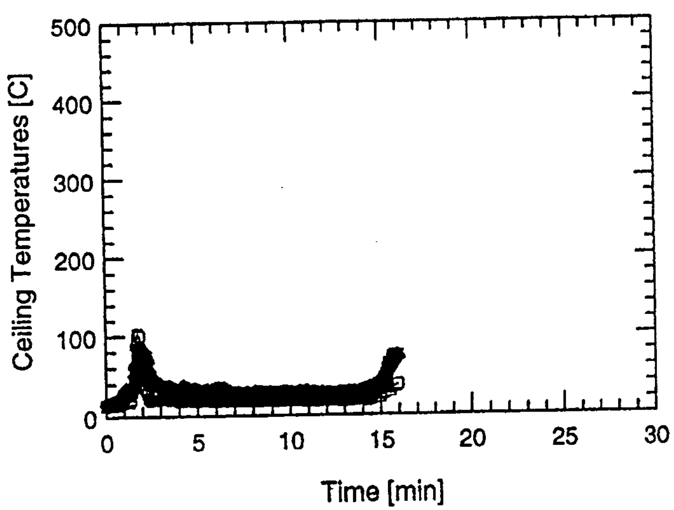
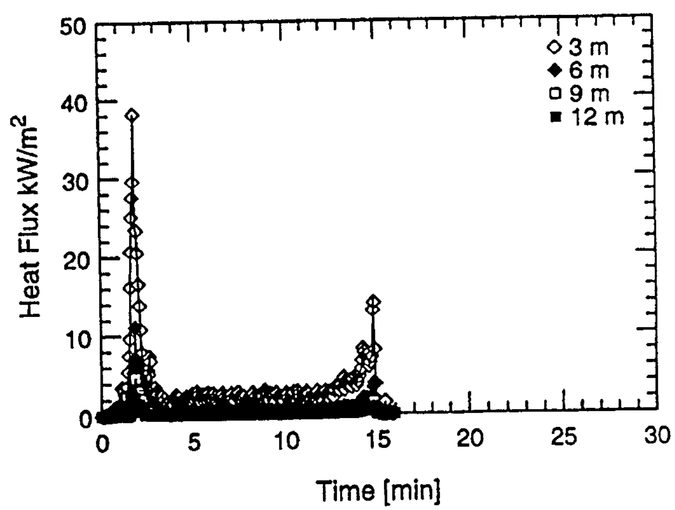


Phase II - Test #7









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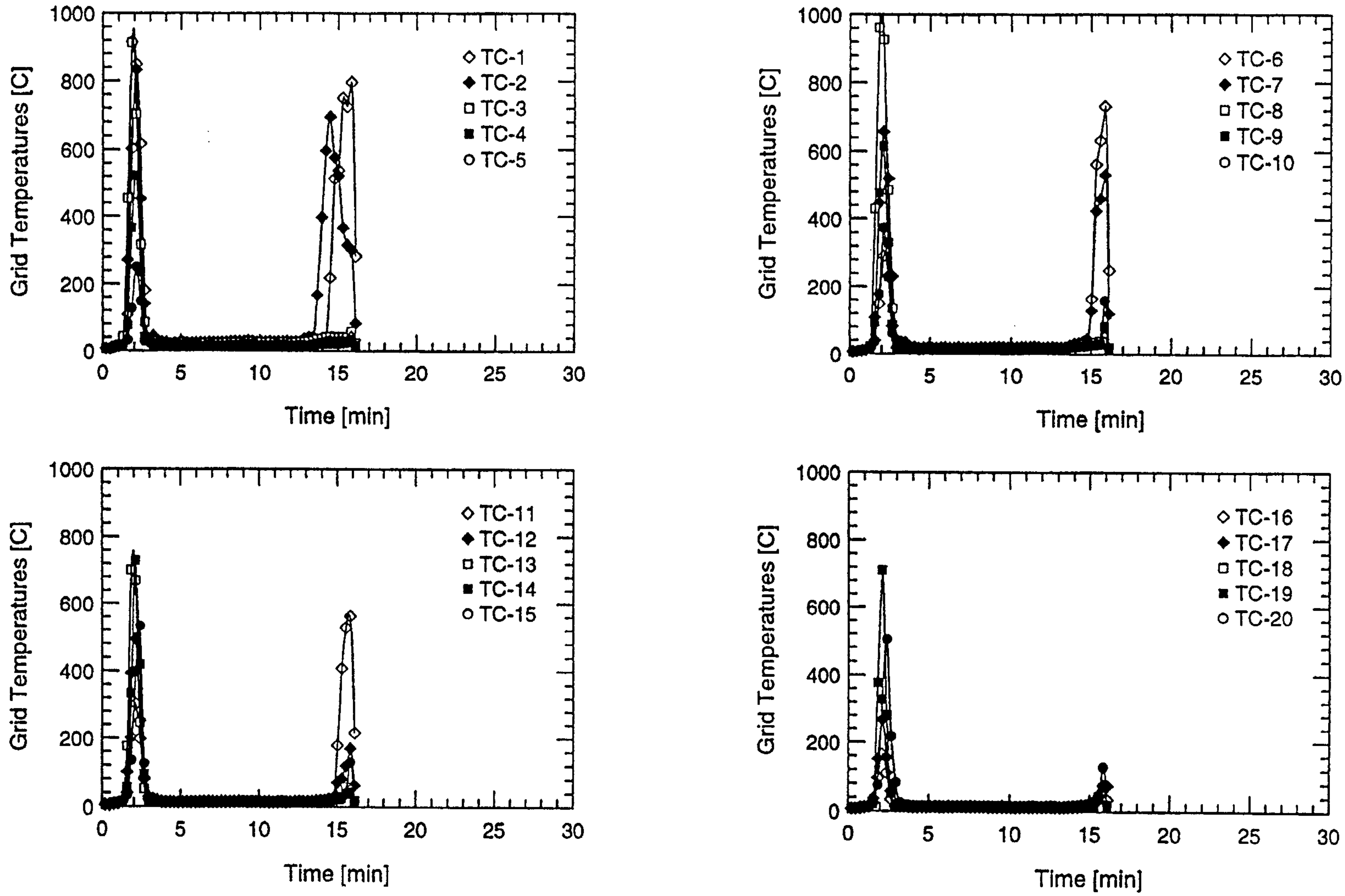

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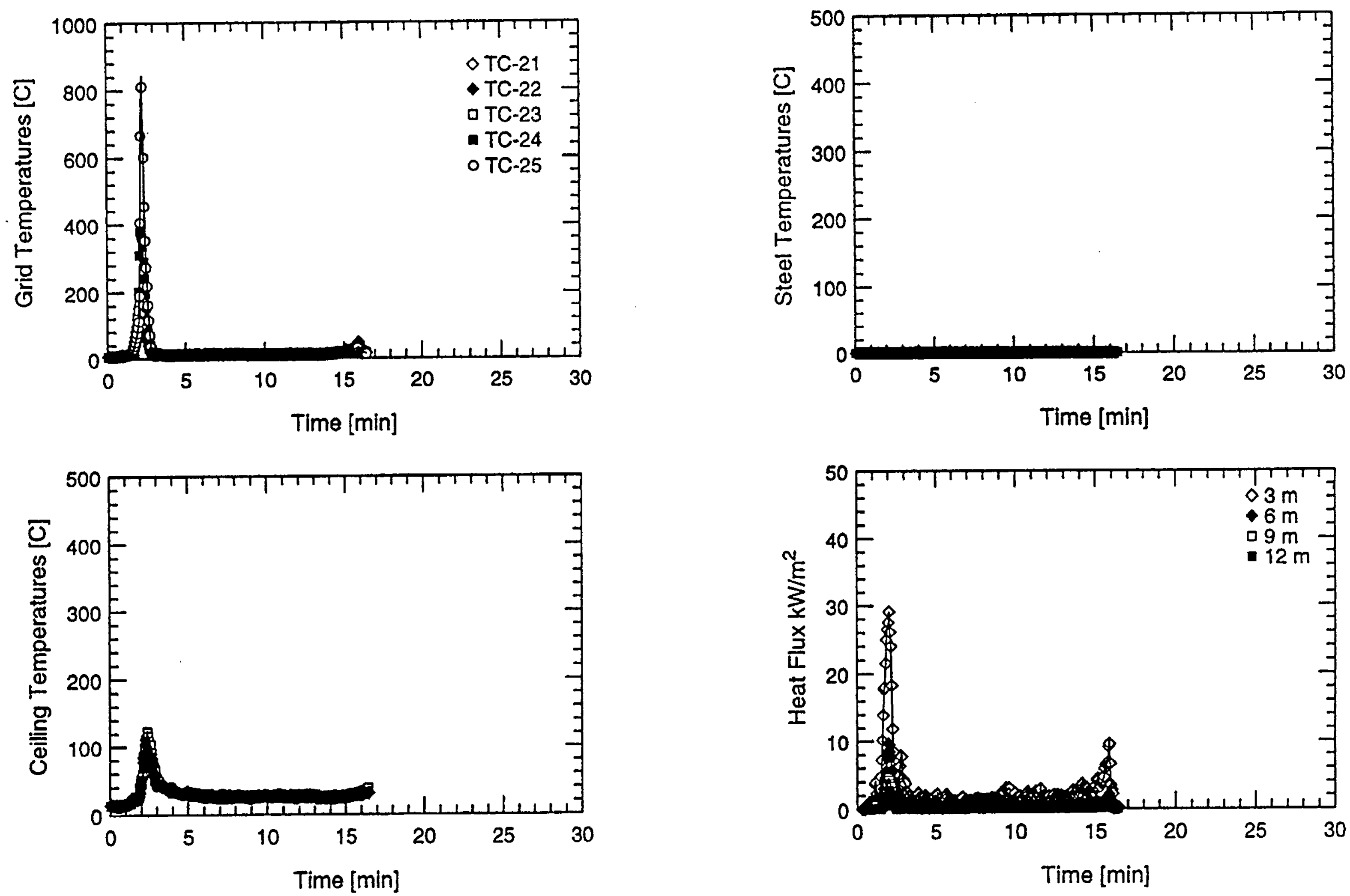
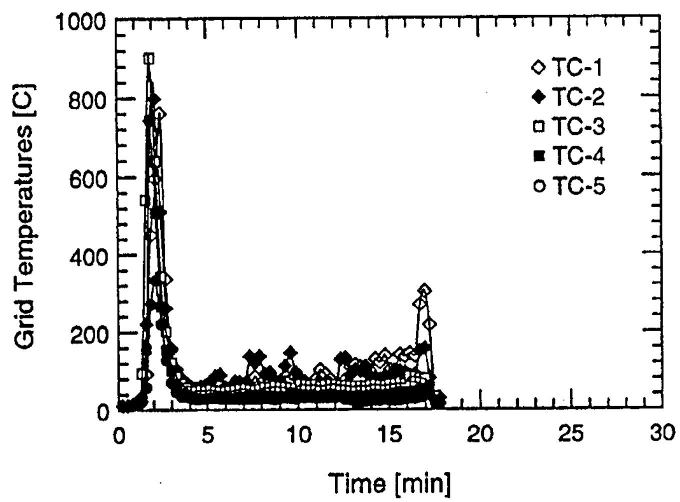
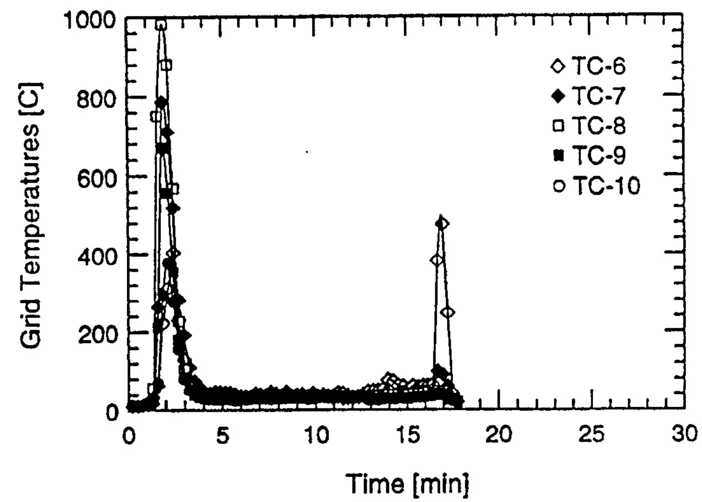
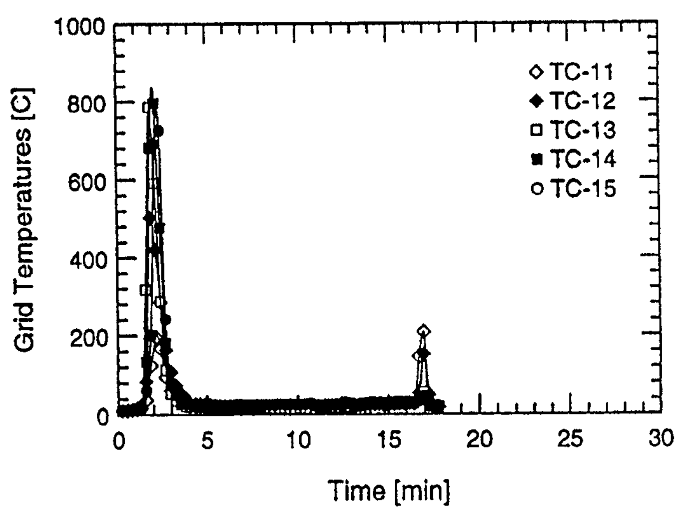
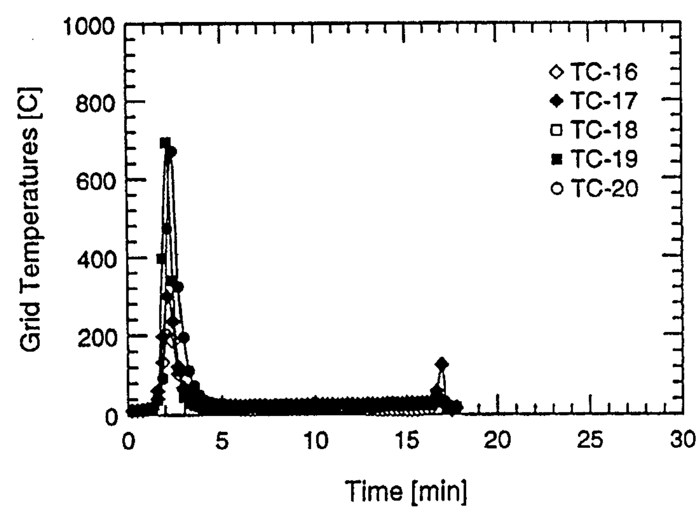


Phase II - Test #8

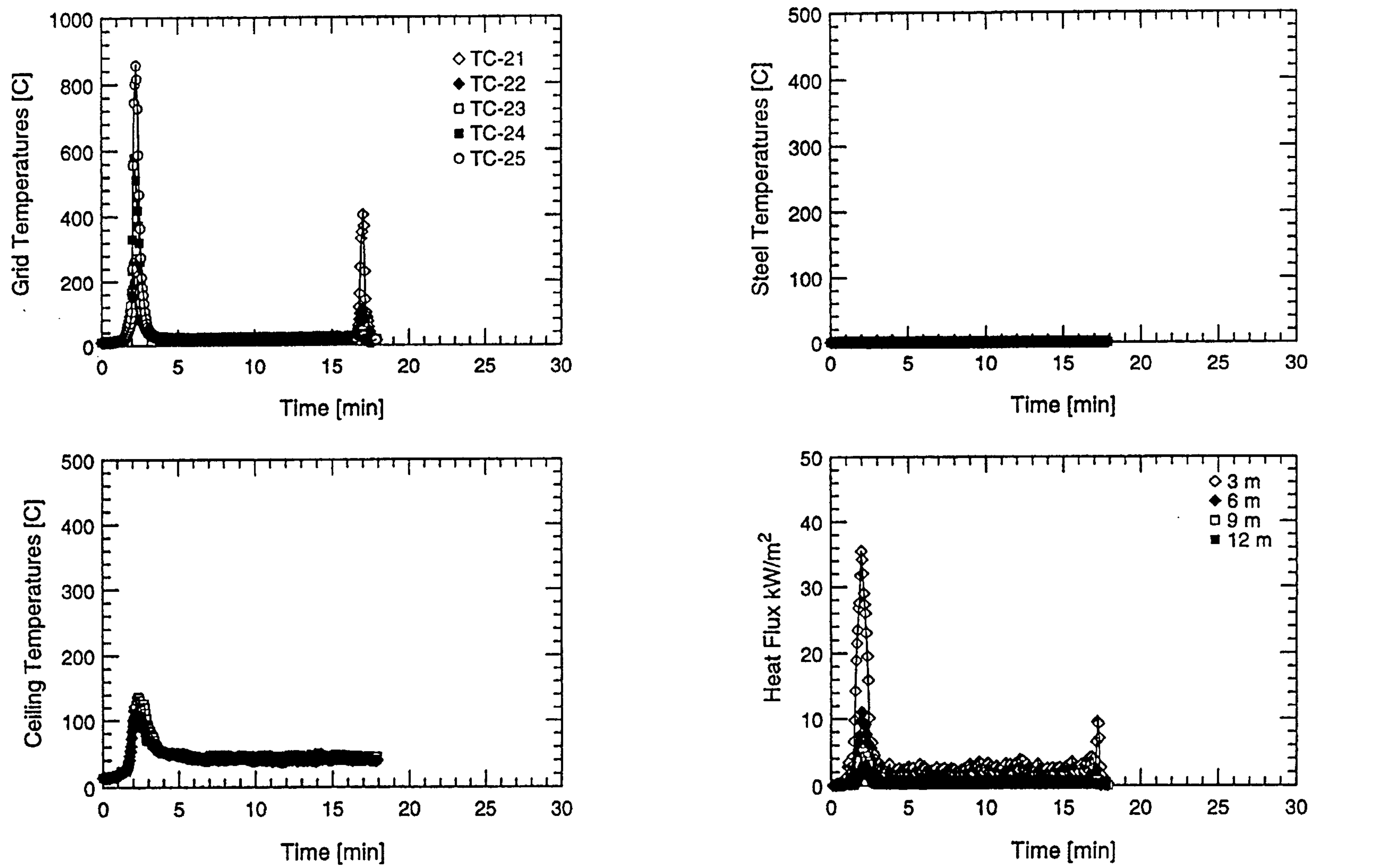




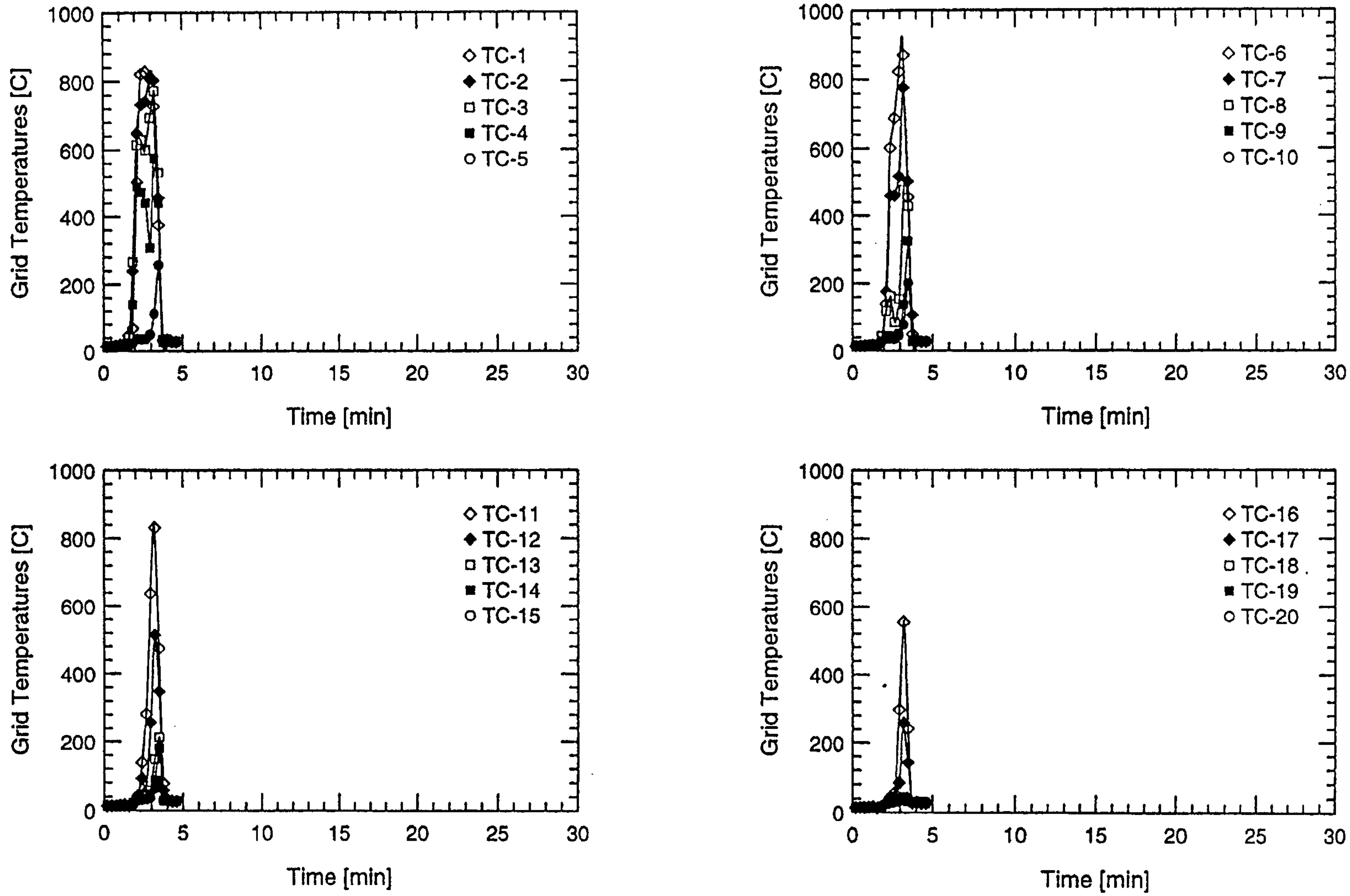




Phase II - Test #9



Phase II - Test #9



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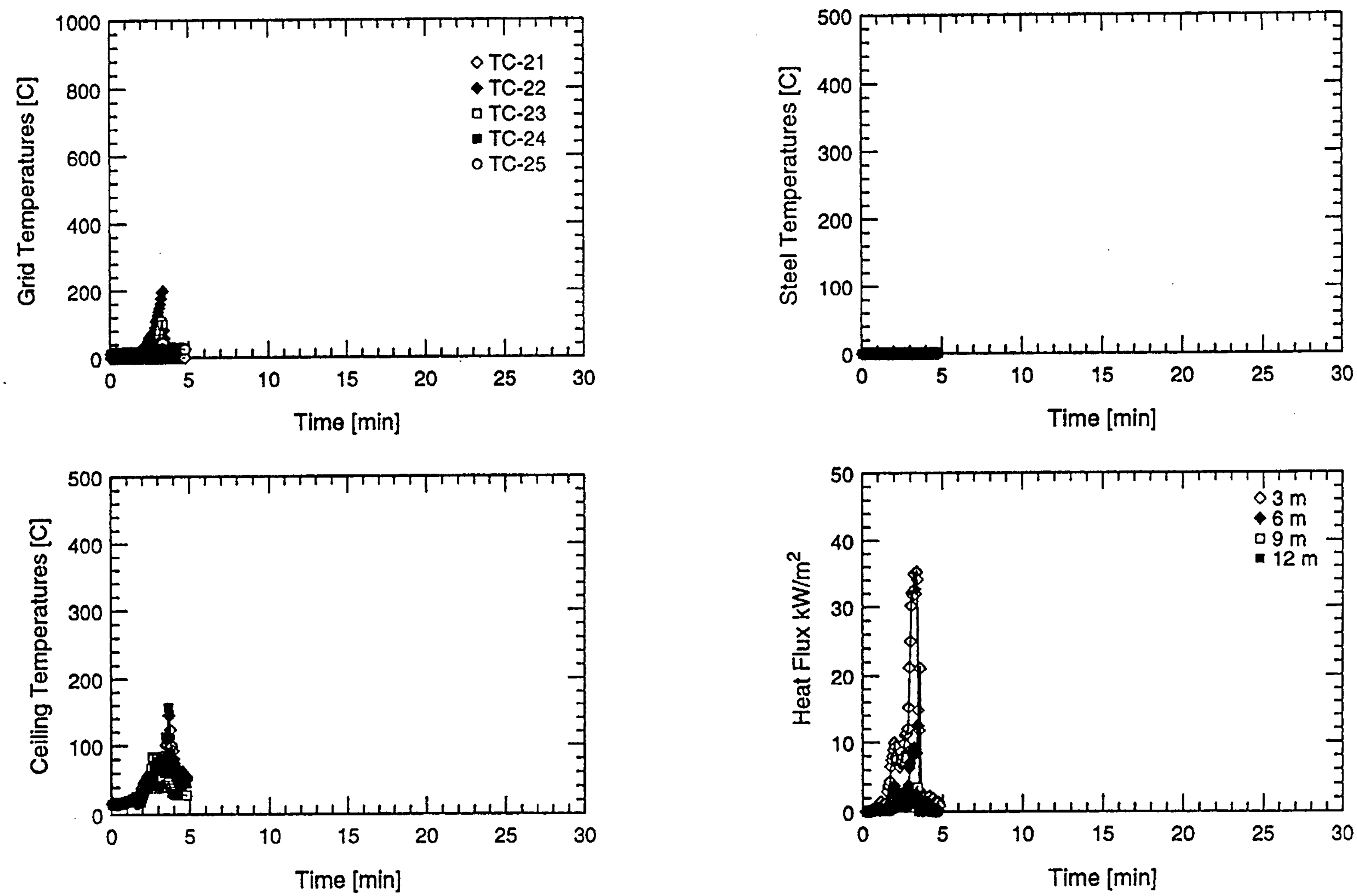

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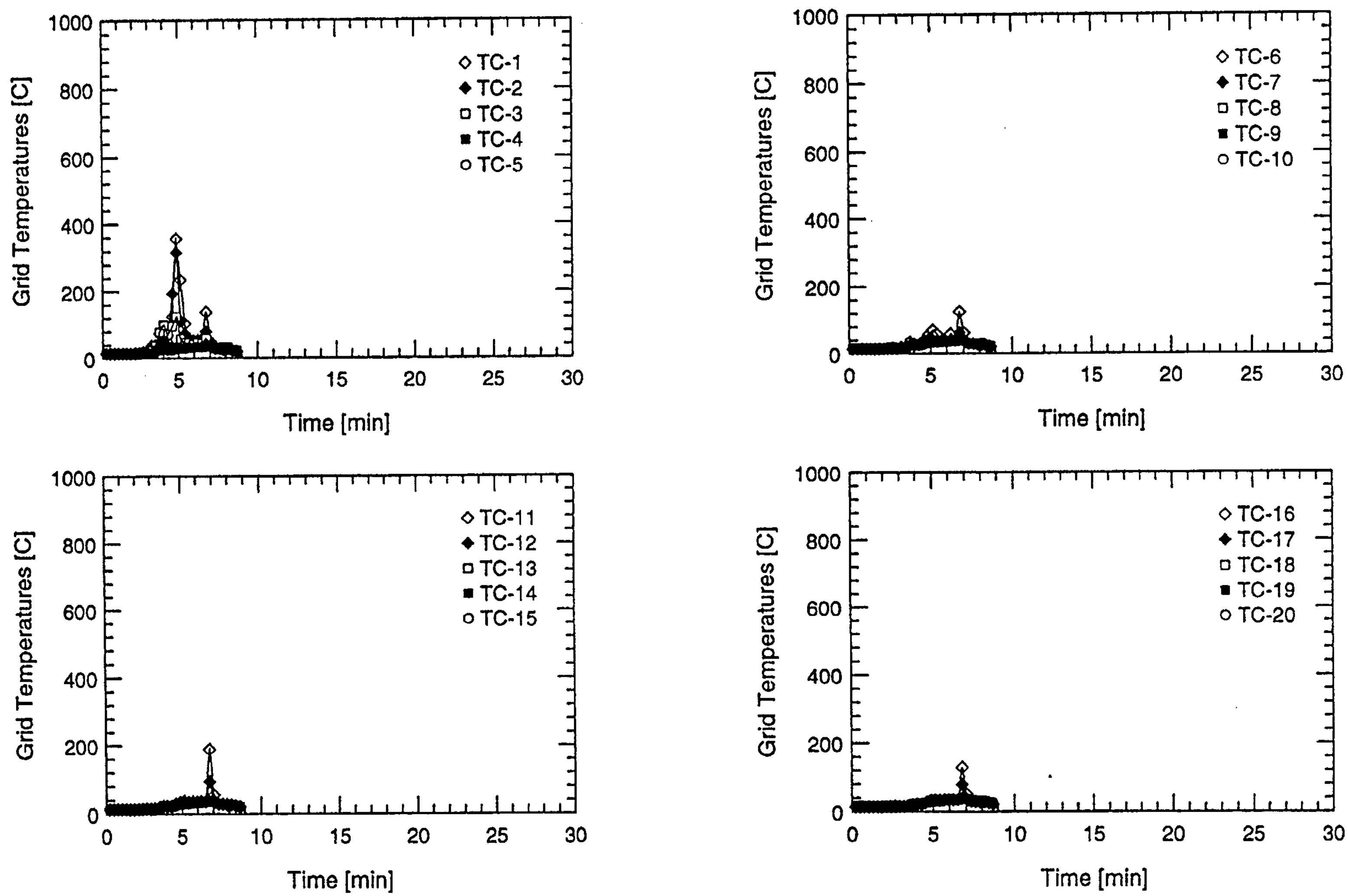

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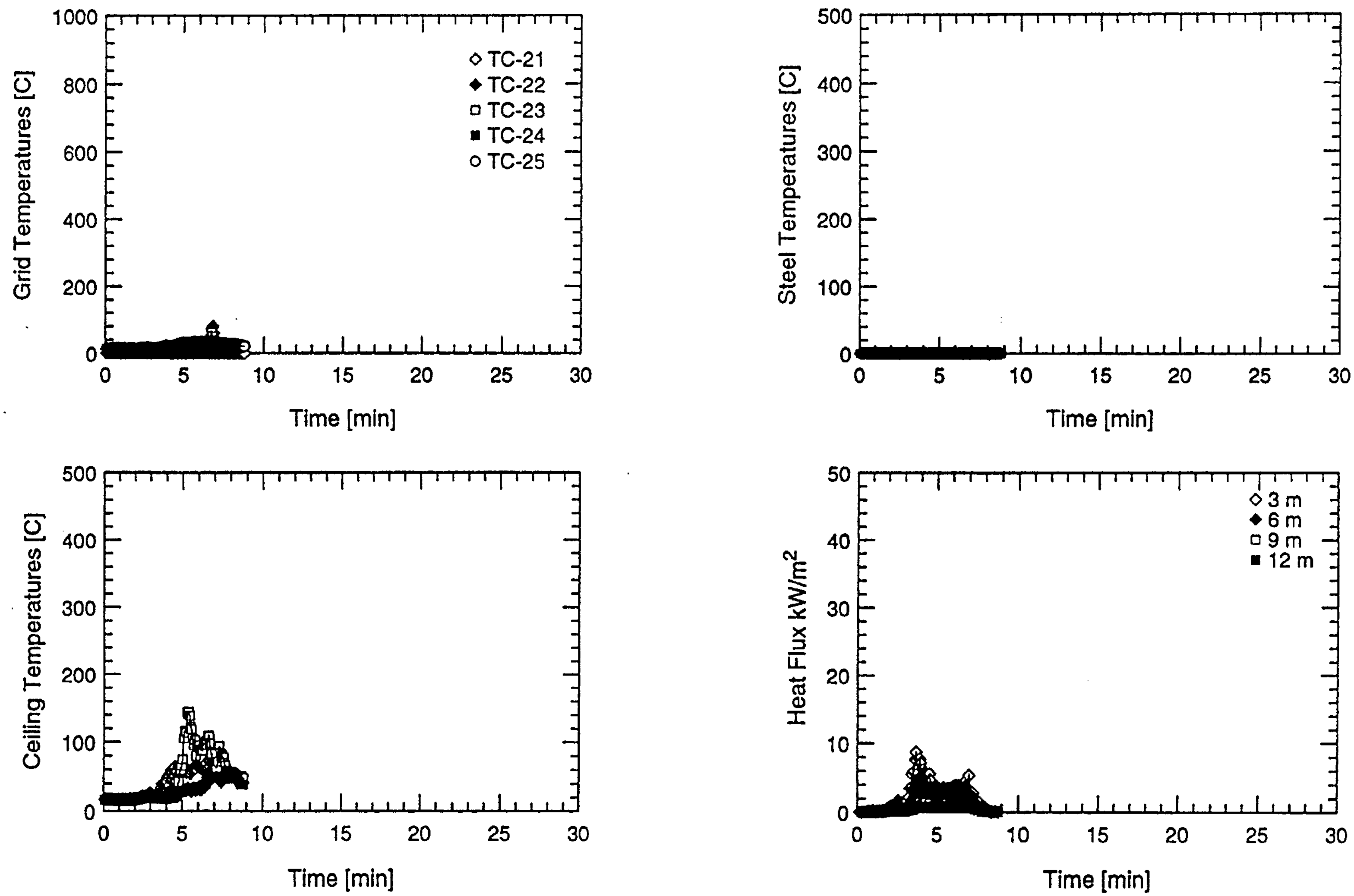

Phase II - Test #11

Appendix B

Fire Scenario Analysis

Fire Scenario Analysis

The quantity of fuel burned in the fire apparatus was determined based on the ratio of radiation measured with only the apparatus burning (shortly after the spill fire was extinguished) to the value recorded when the spill fire was at it's maximum size.

For example, during Fire Scenario 1, the maximum radiation measured at a distance of 3.0 m (10 ft) from the fire was typically 35 kW/m^2. This value corresponds to the steady-state burning of all the fuel being pumped into the apparatus. The resulting heat release for this fire is 22.5 MW (based on the heat of combustion of the fuel). Immediately after the spill fire was extinguished, the measured radiation dropped to 17.5 kW/m^2 which is one half of the maximum value. For estimating purposes, it can be assumed that one half of the fuel was being burned in the apparatus and the other half spilled on the deck.

Sample calculations for the three fire scenarios are as follows:

Fire Scenario 1

$$\dot{q}''_{(22.5\ MW)} = 35\ kW/m^2$$

$$\dot{q}''_{(ext)} = 17.5\ kW/m^2$$

$$\dot{V}_{APP_{fuel}} = 38\ Lpm\ \frac{17.5\ kW/m^2}{35\ kW/m^2} = 19\ Lpm \quad \text{burned in the fire apparatus}$$

$$\dot{V}_{spill_{fuel}} = 38\ Lpm - 19\ Lpm = 19\ Lpm \quad \text{spilled on the deck}$$

Fire Scenario 2

$$\dot{q}''_{(22.5\ MW)} = 35\ kW/m^2$$

$$\dot{q}''_{(ext)} = 7\ kW/m^2$$

$$\dot{V}_{APP_{fuel}} = 38\ Lpm\ \frac{7\ kW/m^2}{35\ kW/m^2} = 7.6\ Lpm \quad \text{burned in the fire apparatus}$$

$$\dot{V}_{spill_{fuel}} = 57\ Lpm - 7.6\ Lpm = 49.4\ Lpm \quad \text{spilled on the deck}$$

Fire Scenario 3

$$\dot{q}''_{(22.5\ MW)} = 35\ kW/m^2$$

$$\dot{q}''_{(ext)} = 1.75\ kW/m^2$$

$$\dot{V}_{APP_{fuel}} = 38\ Lpm\ \frac{1.75\ kW/m^2}{35\ kW/m^2} = 1.9\ Lpm \quad \text{burned in the fire apparatus}$$

$$\dot{V}_{spill_{fuel}} = 38\ Lpm - 1.9\ Lpm = 36.1\ Lpm \quad \text{spilled on the deck}$$

The radiation exposure at the base of the fire apparatus ramp was estimated using the point source model developed in Section 6.6. The radiation measured at the 3.0 m (10 ft) location immediately after extinguishment was scaled to a distance of 1.5 m (5 ft). These calculations are shown as follows:

$$FireScenario\ 1 \qquad 17.5\ kW/m^2 \left(\frac{(3\ m)^2}{(1.5\ m)^2}\right) = 70\ kW/m^2$$

$$FireScenario\ 2 \qquad 7\ kW/m^2 \left(\frac{(3\ m)^2}{(1.5\ m)^2}\right) = 28\ kW/m^2$$

$$FireScenario\ 3 \qquad 1.75\ kW/m^2 \left(\frac{(3\ m)^2}{(1.5\ m)^2}\right) = 7\ kW/m^2$$

Appendix C

Statistical Data Analysis

Statistical Analysis of Fire Test Data

1.0 Introduction

An analysis was performed to quantify the effect of various system parameters on the test results. The overall goal of this analysis was to determine if a statistically significant difference exists between the measured means of the test results for a given set of variables. This study examines several sets of mean comparisons. The first set of two means analyzed was the time to 90% extinguishment for the two different fuels used in the tests, JP-5 and JP-8. In addition to the 90% extinguishment times, the 100% extinguishment and the burnback times were also analyzed to determine if the mean values for JP-5 and JP-8 were statistically different.

The sprinkler application rates were also examined using this same technique. The control, extinguishment and burnback time means were examined with respect to the sprinkler application rates. The mean times for the various application rates were compared to determine if the overhead sprinklers had any effect of the firefighting capabilities of the system.

2.0 Methodology

Two types of analysis were used to evaluate the test results. First a two sample t-test was used to evaluate the effect a system parameter variation had on measured mean test results (i.e. type of fuel, JP-5 or JP-8, verses burnback time). A two sample t-test calculates a t-statistic and then compares this value to a table of probabilities. The corresponding probability used in this case was for 90% confidence level. The probability reported indicates if there is a statistical difference between two means for a given pair of variables [1c]. This type of test was also used to determine if sprinkler system operation (i.e., any application rate versus no sprinkler system operation) had any effect on the observed mean values.

The second type of analysis performed was an analysis of variance (ANOVA). The analysis is performed on the three level parameters (i.e., sprinkler application rates 0.0, 6.5 and 10.2 Lpm/m^2 (0.0, 0.16 and 0.25 gpm/ft^2) in order to evaluate the net effect of the variation. This type of analysis quantifies the overall effect one parameter has on the observed variance and mean values for a set of measurements. This type of level effect analysis of a mean value greatly diminishes the influence of uncontrolled parameters in an experiment [1c]. The results of an ANOVA are the mean value for a particular variable and a combination of variables, the sum-of squares, the mean square, the F-ratio and the confidence probability. This information allows conclusions to be drawn as to the effects test variables have on the mean variance of the results. While conclusions regarding the ranking of observed influence are not appropriate for this type of analysis, the ANOVA will clearly illustrate any impact the fuel type or sprinkler application rate has on the capabilities of the system.

3.0 Results and Analysis

Fuel Type Effects

A two sample t-test for the mean times for 90% extinguishment, 100% extinguishment and burnback was conducted. The tabular results are presented in Table C1. In each case, the calculated t-statistic and corresponding probability values illustrate the difference in the observed mean values. The mean values for 90 and 100% extinguishment and burnback times are statistically different at the 90% confidence level. The probability values are less than 0.10 and, therefore, indicate that JP-5 and JP-8 have different effects on extinguishment and burnback times.

Sprinkler System Effects

The ANOVA for the sprinkler application rates of 0.0, 6.5 and 10.2 Lpm/m^2 (0.0, 0.16 and 0.25 gpm/ft^2) showed no significant impact on the mean times of 90 and 100% extinguishment or on burnback. The calculated F-Ratios have corresponding probabilities greater than the 0.10 indicating that the results of these tests were statistically similar for a 90% confidence level. These results are presented in tabular form in Table C-2.

An analysis was then performed to determine if *any* sprinkler application rate had an effect on the system capabilities. To accomplish this the means for two groups were calculated and analyzed. The mean times for 90 and 100% extinguishment and burnback were calculated for cases of sprinkler system operation verses non-operation. These results are presented in Table C-2. In each case the difference in the means is not significant to the 90% confidence level.

Test 4 of Phase II was determined to be an outlier with respect to the reported burnback time of 13 minutes. Chaurenets criterion [2c] was used to determine that the data point should be rejected. The measurement was 2.4 standard deviations away from the mean value for the Phase II tests. The chance of this being random is less than 1.2%. This data point was excluded from the analysis.

Table C-1. Result Summary: Fuel Type on 90 and 100% Extinguishment and Burnback Times

Fuel	90% Extinguishment			100% Extinguishment			Burnback		
	Mean Time/Std. Deviation (sec)	t-Statistic	Probability (p)	Mean Time/Std. Deviation (sec)	t-Statistic	Probability (p)	Mean Time/Std. Deviation (min)	t-Statistic	Probability (p)
JP-5	23.2 / 8.4	-3.3	0.005	36.3 / 9.9	-3.5	0.006	5.2 / 1.4	2.09	0.053
JP-8	36.1 / 7.8			58.1 / 14.2			4.1 / 0.69		

Table C-2. Result Summary: Sprinkler Operation on Extinguishment and Burnback Times

Sprinkler Application Rate Lpm/m^2	90% Extinguishment			100% Extinguishment			Burnback		
	Mean Time/Std. Deviation (sec)	F-Ratio or t-Statistic	Probability (p)	Mean Time/Std. Deviation (sec)	F-Ratio or t-Statistic	Probability (p)	Mean Time/Std. Deviation (min)	F-Ratio or t-Statistic	Probability (p)
0	32.4 / 4.4	1.75	0.21	45.6 / 7.2	0.17	0.84	5.2 / 0.59	0.39	0.68
6.5	23.9 / 3.3			43.0 / 5.5			4.6 / 0.45		
10.2	32.8 / 4.9			48.8 / 8.2			4.8 / 0.66		
Not Operating	32.4 / 8.9	1.20	0.27	45.6 / 10.1	0.12	0.90	5.2 / 0.84	1.10	0.30
Operating	26.6 / 10.6			44.8 / 17.7			4.6 / 1.4		

4.0 Conclusions

1. The mean time to achieve 90 and 100% extinguishment was less for JP-5 than JP-8. The mean burnback time for JP-5 was greater than the mean burnback time for JP-8. The difference in these mean values for these cases are statistically significant at the 90% confidence level.

2. The Sprinkler application rate had no effect on the firefighting capabilities (extinguishment or burnback) of the system.

5.0 References

1.c. Johnson, R.A. *Miller & Freund's Probability & Statistics for Engineers,* Prentice-Hall, 1994 London, UK.

2.c. Taylor, J.R. *An Introduction to Error Analysis-The Study of Uncertainties in Physical Measurements,* Oxford University Press, 1992 Mill Valley CA.